Crop yield evaluation under controlled drainage in Ohio, United States

E. Ghane, N.R. Fausey, V.S. Shedekar, H.P. Piepho, Y. Shang, and L.C. Brown

Abstract: Controlled drainage (CD) is an important practice for reducing nutrient loading to surface water bodies across the midwestern United States. There may also be a positive crop yield benefit, which could add an incentive for adoption of this practice. The objective of this multienvironment trial was to assess yield stability and yield performance of CD in northwest Ohio, United States. The trial was a split-plot experiment with environments as whole plots (randomization unit). The main plot factor was crop with three levels: corn (Zea mays L.), popcorn (Zea mays L. var. everta), and soybean (Glycine max [L.] Merr.). The subplot factor was drainage management with two levels: conventional free drainage (FD) and CD. The design of the main plot factor was a completely randomized design. Mixed model analysis showed that CD management produced a statistically greater \( p\)-value = 0.0246 \) crop yield compared to FD management over 23 site-year environments during 2008 to 2011. Interaction between drainage management and crop was not significant, implying that CD management had the same yield-increasing effect for all crops. The CD management provided 3.3%, 3.1%, and 2.1% greater yield for corn, popcorn and soybean, respectively, relative to the FD management. The stability analysis based on 23 environments suggested that the drainage managements were not different in yield stability, though a larger number of environments are needed to make a more accurate assessment of yield stability. Area of influence analysis indicated that CD can provide more profit than FD for relatively flat fields where the influence of CD extends over the entire field. In conclusion, CD provided crop yield advantage over FD across different environments in northwest Ohio.

Key words: free drainage—managed drainage—mixed model—multienvironment trials—on-farm experiment—yield stability

Northwest Ohio is an intensively drained region within the midwestern United States where excess water in the soil profile is removed to accommodate crop growth (Fausey et al. 1995). Water quality and environmental concerns associated with conventional subsurface drainage have heightened interest in restricting the subsurface drainage discharge from cropland to reduce the potential of chemical loss (Evans et al. 1995). This practice, which is known as controlled drainage (CD) (USDA NRCS Ohio 2012), may have crop yield benefits. One of the earliest implementations of this practice was in California, United States, where the water table was raised by installing an elbow on the drainage system outlet with the purpose of investigating denitrification (Willardson et al. 1972). Controlled drainage was mentioned briefly in the Yearbook of Agriculture (Renfro 1955) as being used in organic (muck) soils with subirrigation and for the control of subsidence (Stephens 1955). Petersen (1966) noted the use of a controlled water table to reduce the presence of iron ochre in drains.

Controlled drainage can retain water in the soil profile for plant growth depending on growing season rainfall, distribution, and crop growth stage. Previous on-station trials (Grigg et al. 2004; Fausey 2005; Drury et al. 2009; Delbecq et al. 2012), and on-farm experiments (OFE) (Cicek et al. 2010) have reported the effect of CD on crop yield. Grigg et al. (2004) did not find a significant corn (Zea mays L.) yield difference between CD and free drainage (FD) on a silt loam soil type over a two-year study including both normal and drought years in Louisiana, United States. Fausey (2005) compared corn and soybean (Glycine max [L.] Merr.) yield under CD and FD management on a silty clay soil type over five years in northwest Ohio, United States, and did not find a significant crop yield difference between the two management systems. In Ontario, Canada, the trend was for greater corn and soybean yields for CD compared to FD on a clay loam soil type when using nitrogen (N) fertilizer for both corn and soybean in all four years of the study, but the differences were not statistically significant (Drury et al. 2009). Delbecq et al. (2012) used a spatial panel regression method to analyze yield monitor data and found significant corn yield improvement for CD compared to FD on average during a five-year study at a site in Indiana, United States, with silt loam and silty clay loam soils. In Ontario, Canada, Cicek et al. (2010) found no significant difference in average corn and soybean yield between CD and FD on a silt loam soil type over four years and across four sites using a conventional paired \( t\)-test. However, CD was reported to produce an average of 3% and 4% greater yield for corn and soybean, respectively.

On-station experiments have also reported the effect of CD on crop yield (Westrom and Messing 2007; Ramoska et al. 2011). In these studies, observations were comprised of repeated measurements taken from the same experimental unit (i.e., pseudoreplication), which resulted in the lack of independence (Johnson 2006). Therefore, inference of the CD effect on crop yield is questionable due to the lack of true replication and randomization (Piepho et al. 2011). Smith and Kellman (2011) also reported on the influence of CD on corn yield but again without replication. On-farm experiments have gained interest due to the development of spatially referenced yield monitors where data can be obtained at small spatial resolution (Piepho et al. 2011). Such OFE, when carried out at different locations for several years, can provide...
valuable conclusions pertaining to the target region. These OFE are called multienvironment trials (MET). The conventional analysis of variance (ANOVA) has been shown to be unsuitable for MET analysis (Coe 2007; Hu and Spilke 2011), while mixed model analysis has been proven beneficial for MET data (Virk et al. 2009; Raman et al. 2011). One difference between the conventional ANOVA and the mixed model analysis is that the former requires homogeneous variance while the latter allows for heterogeneous variance. Mixed models have been used for the analysis of MET data (Dai et al. 2012; Ruyman et al. 2012) and evaluation of yield stability across environments (Raman et al. 2011; Lal 2012).

The yield variance of a farming practice (e.g., CD) across environments can be a measure of its stability (Piepho 1998), though there has been no study evaluating the yield stability of CD. Furthermore, considering the importance of mixed model analysis of MET data, no study has taken this approach to evaluate the effect of CD on crop yield. If CD design, use, and management recommendations are to be made on the regional level, there is need to assess and quantify the average performance of this practice across a broad range of conditions. The objective of this study was to evaluate yield stability and yield benefit of CD practice in northwest Ohio.

**Materials and Methods**

**Description of Sites.** The study was conducted as an OFE at seven demonstration sites on private farms located in northwest Ohio, United States, and yield data were collected from 2008 to 2011 (figure 1). Description of the seven sites used in the analysis is summarized in table 1. The majority of the area at each site had a very poorly drained soil type with minor areas of somewhat poorly drained soil type. All of the sites are subsurface drained with 100 mm (4 in) drains installed at a depth of 0.8 to 1.2 m (2.5 to 4 ft). Lateral spacing at each site was the same in the entire field. Each site had a somewhat different crop rotation pattern, but generally corn and soybean rotation was the most common cropping practice.

**Experimental Design and Treatments.** The MET approach was adopted to evaluate the crop yield impact of implementing CD. Yield data were collected for four years and from seven sites (farms), which were randomly selected from the intensively drained target region of northwest Ohio. Each site-year hereafter will be referred to as an environment. The trial was a split-plot experiment with environments as whole plots (randomization unit). The allocation of crops to environments was based on the decision of the farmers. Therefore, the resulting data structure is analogous to that of a split-plot experiment, and so data were analyzed accordingly. The main plot factor was crop with three levels: corn, popcorn (Zea mays L. var. everta), and soybean. The subplot factor was drainage management with two levels: conventional FD and CD. Each main plot was divided into two subplots (zones) with approximately equal areas, and the two levels of the drainage management factor were randomly allocated to each subplot. The design of the main plot factor was a completely randomized design.

Each environment had its specific weather, crop, and management. Overall, there were 8 environments with corn, 3 environments with popcorn, and 12 environments with soybean (table 2). Van Wert 2008 to 2010 environments were not included in the data analysis since flow was found to be bypassing the control structure, most likely because an antiseep collar was not installed. The outlet pipe was repaired, and an antiseep collar was installed on June 2011 before the implementation of CD. The Henry 2008 and Auglaize-SE 2009 data were not included because different cropping man-

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*Figure 1*

Location of the sites in northwest Ohio, United States.
agments were applied to the subplots in these environments.

The lateral drains from each zone discharged to a main pipe that was routed through an inline water level control structure (Agri Drain Corp., Adair, Iowa) before discharging into the drainage ditch. Within the control structure, stop-logs were used to adjust the outlet elevation to different heights to accommodate the CD goal during different seasons (Frankenberger et al. 2006). Typically, the CD outlet elevation was set approximately 0.3 m (1 ft) below the ground surface after harvest until early April (a few weeks before planting). The outlet

Table 1
Physical characteristics and long term precipitation of the sites in northwest Ohio, United States.

<table>
<thead>
<tr>
<th>Description</th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
<th>Site 4</th>
<th>Site 5</th>
<th>Site 6</th>
<th>Site 7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site name</td>
<td>Henry</td>
<td>Auglaize-E</td>
<td>Hardin-NW</td>
<td>Defiance</td>
<td>Auglaize-SE</td>
<td>Van Wert</td>
<td>Hardin-N</td>
</tr>
<tr>
<td>Relief (m)*</td>
<td>0.45</td>
<td>0.15</td>
<td>1.17</td>
<td>1.10</td>
<td>0.47</td>
<td>0.30</td>
<td>3.36</td>
</tr>
<tr>
<td>Area of controlled drainage zone (ha)</td>
<td>15.0</td>
<td>7.7</td>
<td>6.3</td>
<td>8.1</td>
<td>7.2</td>
<td>4.5</td>
<td>7.1</td>
</tr>
<tr>
<td>Area of free drainage zone (ha)</td>
<td>14.2</td>
<td>11.7</td>
<td>5.3</td>
<td>7.7</td>
<td>7.3</td>
<td>3.6</td>
<td>5.3</td>
</tr>
<tr>
<td>Dominant soil type</td>
<td>Mermill loam</td>
<td>Milford silty loam</td>
<td>Blountsilt loam</td>
<td>Paulding clay</td>
<td>Montgomery silty clay</td>
<td>Hoytville Blountsilt clay loam</td>
<td></td>
</tr>
<tr>
<td>30-year growing season mean precipitation (mm)†</td>
<td>453</td>
<td>499</td>
<td>451</td>
<td>462</td>
<td>481</td>
<td>485</td>
<td>446</td>
</tr>
<tr>
<td>Lateral spacing (m)</td>
<td>10</td>
<td>15</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>12</td>
<td>15</td>
</tr>
</tbody>
</table>

* The elevation increase from the soil surface at the controlled drainage control structure to the highest point in the controlled drainage zone.
† 1981 to 2010 mean precipitation of the months of May through September.

Table 2
Mean crop yield of drainage managements and growing season rainfall for all environments (site and year combination).

<table>
<thead>
<tr>
<th>Environment</th>
<th>Site</th>
<th>Year</th>
<th>Crop</th>
<th>Planting date</th>
<th>CD yield (Mg ha⁻¹)</th>
<th>FD yield (Mg ha⁻¹)</th>
<th>Rainfall (mm)*</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Henry</td>
<td>2009</td>
<td>Corn</td>
<td>May 19</td>
<td>13.50</td>
<td>12.80</td>
<td>265</td>
</tr>
<tr>
<td>2</td>
<td>Henry</td>
<td>2010</td>
<td>Soybean</td>
<td>May 30</td>
<td>3.13</td>
<td>3.17</td>
<td>368</td>
</tr>
<tr>
<td>3</td>
<td>Henry</td>
<td>2011</td>
<td>Popcorn</td>
<td>June 1</td>
<td>6.77</td>
<td>6.34</td>
<td>686</td>
</tr>
<tr>
<td>4</td>
<td>Auglaize-E</td>
<td>2008</td>
<td>Soybean</td>
<td>June 9</td>
<td>3.16</td>
<td>3.03</td>
<td>506</td>
</tr>
<tr>
<td>5</td>
<td>Auglaize-E</td>
<td>2009</td>
<td>Popcorn</td>
<td>April 27</td>
<td>5.59</td>
<td>5.60</td>
<td>307</td>
</tr>
<tr>
<td>6</td>
<td>Auglaize-E</td>
<td>2010</td>
<td>Soybean</td>
<td>May 15</td>
<td>4.53</td>
<td>4.50</td>
<td>433</td>
</tr>
<tr>
<td>7</td>
<td>Auglaize-E</td>
<td>2011</td>
<td>Popcorn</td>
<td>May 17</td>
<td>3.77</td>
<td>3.69</td>
<td>641</td>
</tr>
<tr>
<td>8</td>
<td>Hardin-NW</td>
<td>2008</td>
<td>Corn</td>
<td>May 29</td>
<td>7.55</td>
<td>6.61</td>
<td>365</td>
</tr>
<tr>
<td>9</td>
<td>Hardin-NW</td>
<td>2009</td>
<td>Soybean</td>
<td>May 18</td>
<td>3.86</td>
<td>3.70</td>
<td>305</td>
</tr>
<tr>
<td>10</td>
<td>Hardin-NW</td>
<td>2010</td>
<td>Corn</td>
<td>April 20</td>
<td>12.84</td>
<td>12.17</td>
<td>431</td>
</tr>
<tr>
<td>11</td>
<td>Hardin-NW</td>
<td>2011</td>
<td>Soybean</td>
<td>June 2</td>
<td>4.45</td>
<td>4.36</td>
<td>604</td>
</tr>
<tr>
<td>12</td>
<td>Defiance</td>
<td>2008</td>
<td>Soybean</td>
<td>May 24</td>
<td>2.22</td>
<td>1.97</td>
<td>441</td>
</tr>
<tr>
<td>13</td>
<td>Defiance</td>
<td>2009</td>
<td>Corn</td>
<td>May 20</td>
<td>9.99</td>
<td>9.76</td>
<td>456</td>
</tr>
<tr>
<td>14</td>
<td>Defiance</td>
<td>2010</td>
<td>Soybean</td>
<td>June 8</td>
<td>2.86</td>
<td>2.67</td>
<td>445</td>
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<tr>
<td>15</td>
<td>Defiance</td>
<td>2011</td>
<td>Soybean</td>
<td>June 5</td>
<td>3.19</td>
<td>3.13</td>
<td>583</td>
</tr>
<tr>
<td>16</td>
<td>Auglaize-SE</td>
<td>2008</td>
<td>Corn</td>
<td>May 1</td>
<td>13.50</td>
<td>12.69</td>
<td>430</td>
</tr>
<tr>
<td>17</td>
<td>Auglaize-SE</td>
<td>2010</td>
<td>Corn</td>
<td>April 19</td>
<td>13.64</td>
<td>13.59</td>
<td>431</td>
</tr>
<tr>
<td>18</td>
<td>Auglaize-SE</td>
<td>2011</td>
<td>Soybean</td>
<td>May 10</td>
<td>3.04</td>
<td>3.34</td>
<td>499</td>
</tr>
<tr>
<td>19</td>
<td>Van Wert</td>
<td>2011</td>
<td>Soybean</td>
<td>June 4</td>
<td>4.10</td>
<td>4.05</td>
<td>576</td>
</tr>
<tr>
<td>20</td>
<td>Hardin-N</td>
<td>2008</td>
<td>Soybean</td>
<td>May 27</td>
<td>2.34</td>
<td>2.24</td>
<td>446</td>
</tr>
<tr>
<td>21</td>
<td>Hardin-N</td>
<td>2009</td>
<td>Corn</td>
<td>May 13</td>
<td>9.94</td>
<td>10.27</td>
<td>270</td>
</tr>
<tr>
<td>22</td>
<td>Hardin-N</td>
<td>2010</td>
<td>Soybean</td>
<td>May 10</td>
<td>3.81</td>
<td>3.69</td>
<td>444</td>
</tr>
<tr>
<td>23</td>
<td>Hardin-N</td>
<td>2011</td>
<td>Corn</td>
<td>June 2</td>
<td>12.99</td>
<td>13.05</td>
<td>723</td>
</tr>
</tbody>
</table>

Notes: CD = controlled drainage. FD = free drainage.
* Growing season rainfall includes the months of May through September.
Yield Data Acquisition. The yield data files from the farmers' spatially referenced yield monitor were processed using SMS Advanced version 11.5 (Ag Leader Technology, Ames, Iowa). In order to improve data quality, the processed data were exported to Yield Editor, version 2.0.2 (USDA ARS 2012), for the removal of erroneous yield data points (Drummond 2011). The importance of improving the quality level of the yield monitor data on making inferences has been stated by Griffin et al. (2008). The filtering criteria used were start pass delay, end pass delay, minimum swath width, and minimum and maximum yield. A start and end pass delay of 2 to 8 yield points was used depending on each site. A minimum swath width equal to the width of the combine swatch was used. An identical filtering criterion was performed on both zones at each site. A minimum and maximum yield of 1.88 and 18.83 Mg ha\(^{-1}\) (30 and 300 bu ac\(^{-1}\)), respectively, for corn; 1.35 and 6.73 Mg ha\(^{-1}\) (20 and 100 bu ac\(^{-1}\)), respectively, for soybean; and 1.681 and 8.967 Mg ha\(^{-1}\) (1,500 and 8,000 lb ac\(^{-1}\)), respectively, for popcorn were used for all environments. Following the filtering process, the data were exported to ArcMap version 10.1 (ESRI Inc., Redlands, California) where the arithmetic mean of the yield data of each zone was calculated and submitted to the MET statistical analysis.

Statistical Analysis. The statistical model of the yield, \(y_{ijk}\), for the split-plot experiment with the main plot factor laid out as a completely randomized design is

\[
y_{ijk} = \mu + \alpha_i + d_j + c_{ij} + \varepsilon_{ijk} \quad (1)
\]

where \(\mu\) is the general mean, \(\alpha_i\) is the main effect for the \(i\)th crop, \(d_j\) is the main effect for the \(j\)th drainage management, \(c_{ij}\) is the interaction between the \(i\)th crop and the \(j\)th drainage management, and \(\varepsilon_{ijk}\) is the environment main effect which represents the main plot error of the model, and \(\varepsilon_{ijk}\) is comprised of both the drainage management subplot error and interaction of treatment factors with the environment.

A combination of a mixed-model and stability analysis was performed where environment was considered as a random factor, and drainage management, crop, and their interactions were fixed factors. Since there was no replication in each environment, the SAS code for means developed by Piepho (1999) was used to fit the variance-covariance structures (stability models) using the MIXED procedure of SAS 9.3 (SAS Institute Inc. 2011).

Stability analysis was performed by modeling heterogeneity of variance in the residual term \(\varepsilon_{ijk}\) (table 3). Specifically, heterogeneity of variance with respect to crop and drainage management was considered. The residual variance was modeled additively on the logarithmic scale (Frensham et al. 1997; Piepho 2009).

Model 1 assumes a constant variance and hence no stability differences. This implies a compound symmetry variance-covariance structure for observations from the same environment. This model is essentially identical to the ANOVA mixed model.

Models 2 and 3 correspond to Shukla’s (1972) stability variance model, replacing crops or drainage managements for varieties, respectively. The management with the smaller stability variance is considered as most stable.

Model 4 can be regarded as a two-way extension of Shukla’s model (Frensham et al. 1997). This model incorporates both heterogeneity of variances between drainage managements and heterogeneity of variances between crops.

It should be noted that model 3 is equivalent to other stability models, such as the environmental variance model and Finlay-Wilkinson regression model (Piepho 1999), because there are only two different drainage managements.

Estimation of the variance components was performed by the restricted maximum likelihood method. The selection of the most appropriate stability model was done using the Akaike’s Information Criterion (AIC) in which the model with the smaller AIC is preferred (Wollinger 1993; Hu and Spilke 2011). Since the compound symmetry model (model 1) is nested within all other stability models, the likelihood ratio test (LRT) was employed to test the null hypothesis that the stability models under consideration are not different from the compound symmetry model (Greene 2012).

In other words, the LRT reveals whether the stability models are significantly more suitable than the compound symmetry model. The LRT statistic is as follows:

\[
LRT = -2(LL_{CS} - LL_s),
\]

where \(LL_{CS}\) and \(LL_s\) are the maximum restricted log-likelihoods for the compound symmetry model and the selected stability model, respectively. The LRT statistic has a chi-squared distribution with degree of freedom equal to the difference in the number of free parameters of the two models. For example, the stability variance model for crops (model 2) has three additional parameters (\(\alpha_c\), \(\alpha_d\), and \(\alpha_{cd}\)) compared to the compound symmetry model, but the restriction \(\Sigma \alpha_c = 0\) reduces the number of additional free parameters by one because \(\alpha_c\)

<table>
<thead>
<tr>
<th>Number</th>
<th>Stability variance model for var(( \varepsilon_{ijk} ))</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(\sigma^2)</td>
<td>Constant variance</td>
</tr>
<tr>
<td>2</td>
<td>(\sigma^2 = \sigma^2 \exp(\alpha))</td>
<td>Heterogeneity between crops</td>
</tr>
<tr>
<td>3</td>
<td>(\sigma^2 = \sigma^2 \exp(\beta))</td>
<td>Heterogeneity between drainage managements</td>
</tr>
<tr>
<td>4</td>
<td>(\sigma^2 = \sigma^2 \exp(\alpha + \beta))</td>
<td>Heterogeneity for both crops and drainage managements</td>
</tr>
</tbody>
</table>

Notes: \(\varepsilon_{ijk}\) residual term, \(\sigma^2\) = stability variance for the \(i\)th crop, \(\sigma^2\) = stability variance for the \(j\)th drainage management, \(\sigma^2\) = stability variance for the \(i\)th crop and the \(j\)th drainage management, \(\sigma^2\) = residual variance, \(\alpha_i\) = effect of \(i\)th crop, subject to the restriction \(\Sigma \alpha_i = 0\), \(\beta_j\) = effect of \(j\)th drainage management, subject to the restriction \(\Sigma \beta_j = 0\).
= -\alpha_{1} - \alpha_{2}. Thus, degrees of freedom is equal to two for the LRT statistic of the stability variance model for crops.

The Wald-type F-test constructed by the MIXED procedure was used for the significance test of the fixed effects using the Kenward-Roger method to approximate the denominator degrees of freedom. Model-based estimates of drainage management least square means were computed using the LSMEANS statement. The normality assumption required for the mixed procedure using the restricted maximum likelihood method was confirmed by examining the normal probability plot of residuals. Heterogeneity of the error variance among environments was confirmed by observing a structure in the plot of the residuals against the fitted response. Yield observations made at the same site over different years are quite commonly assumed to be independent.

**Area of Influence.** A similar analysis was performed with the difference being that the mean yield from only the area influenced by CD was used in the mixed model analysis instead of using the mean yield from the whole area of each zone. For the Hardin-NW, Defiance, and Hardin-N sites where there was a relatively large relief across the field (table 1), the yield from the area influenced by CD was used in this analysis. The area of influence in the CD zone is defined by an elevation increase equal to the difference of the water table depth in the CD control structure from the maximum effective root depth (figure 2). The maximum effective root depth used for determining the area of influence was 1.2 m (4 ft) for corn and 0.9 m (3 ft) for soybean (USDA NRCS 1997). Thus, the area of influence is different for each crop at each site. The water table depth was calculated from actual stop-log setting in the CD control structure for each site during the summer when CD was implemented. For the FD zone, the yield points within the same elevation range as the area influenced by CD were used to calculate mean yield. At the Henry, Auglaize-E, Auglaize-SE, and Van Wert sites, the fields were relatively flat, so the area impacted by CD extended over the entire CD zone. Therefore, 12 environments with yield from the area of influence and 11 environments with yield from the whole field, as used in the previous section, were employed to assess the effect of CD on sloping fields. Figure 3 illustrates the calculated zone of influence for the Hardin-NW site with corn.

**Water Level Measurement.** At each site, water level in both of the control structures was measured using a level-watch sensor (Automata, Nevada City, California) or HOBO U20 water level data logger (Onset, Bourne, Massachusetts), which was placed inside a PVC stilling well and lowered to the bottom of each structure. The water level was in reference to the soil surface at the first row of crops, so it represents the water depth. A water level control plan was instituted for each site, but in all cases the plan was altered based on actual planting date, how the farm cooperators wanted to address adverse or expected climatic conditions as they arose, and their level of comfort with risk. Each year when CD was implemented during the growing season, the number of hours the water table was within 1.3 m (4.3 ft) of the soil surface was calculated for each of the two FD and CD zones. The depth of 1.3 m was chosen because it represents the presence of water table near the corn maximum effective root depth (USDA NRCS 1997). The environments with missing water level data from this period were not included in this analysis.

**Stability Analysis.** The LRT indicated statistical significance at \( \alpha = 0.05 \) for model 2 and Shukla two-way extension model 4 (table 4). Hence, the compound symmetry model with constant variance was not appropriate for the analysis because it did not fit the data. The best fitting model out of these two models was model 2 based on the lowest AIC value, which gave a slightly lower AIC value than the Shukla two-way extension model 4. In other words, allowing heterogeneity of variance only between crops slightly improved the data fit to the model compared to the Shukla two-way extension model 4, which allowed heterogeneity for both crop and drainage management. As a result, no significant heterogeneity between drainage management was detected, suggesting that the drainage management are not different.
Table 4
Akaike’s Information Criterion (AIC) and likelihood ratio test (LRT) for different stability models.

<table>
<thead>
<tr>
<th>Stability variance model</th>
<th>AIC</th>
<th>–2LL</th>
<th>LRT</th>
<th>df</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model 1</td>
<td>98.7</td>
<td>94.7</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Model 2</td>
<td>90.2</td>
<td>82.2</td>
<td>12.5</td>
<td>2</td>
<td>0.0019</td>
</tr>
<tr>
<td>Model 3</td>
<td>100.5</td>
<td>94.5</td>
<td>0.2</td>
<td>1</td>
<td>0.6547</td>
</tr>
<tr>
<td>Model 4</td>
<td>92.1</td>
<td>82.1</td>
<td>12.6</td>
<td>3</td>
<td>0.0056</td>
</tr>
</tbody>
</table>

Notes: \(-2LL = -2 \times \text{maximum restricted log-likelihood. LRT} = -2(LL_{CS} - LL_{S})\), where \(LL_{CS}\) and \(LL_{S}\) are the maximum restricted log-likelihoods for the compound symmetry model and the selected stability model, respectively. df = degree of freedom of LRT statistic equal to the difference in the number of free parameters of the compound symmetry model and the selected stability model.

Figure 3
Illustration of the computed area of influence used in the analysis at the Hardin-NW site with corn.

Legend
Area of influence
- Free drainage
- Controlled drainage
Control structures
- Free drainage
- Controlled drainage
Drainage layout
- Free drainage
- Controlled drainage
Contour
- Meter

in yield stability. Nevertheless, the two-way extension of the Shukla model indicated that the yield from the CD management is considerably more stable than that of the FD management for all crops (table 5). The lower yield variation in the CD management could be explained by the more uniform water table across relatively flat fields (Skaggs 1980). More uniform corn and soybean growth for CD relative to FD has also been reported by Cicek et al. (2010), using satellite remote sensing of vegetation indices.

Nevertheless, it is essential to note that the limited number of environments in this study is not adequate to allow a more accurate yield stability assessment. Piepho (1998) indicated that the difficulty of yield stability analysis is the need of a large number of environments to obtain a reliable stability assessment. Therefore, more environments are needed to make a more precise evaluation of yield stability regarding CD and FD drainage managements. To the authors’ knowledge, this MET is the first to evaluate yield stability and mixed model yield analysis of CD.

The parameter estimates for different stability models are summarized in table 5. Based on the best fitting Shukla model 2, corn was the least stable crop (highest stability variance), and soybean was the most stable crop (lowest stability variance). Compared to corn, lower soybean yield variation has also been reported by Williams et al. (2008) over a 20-year study period across 99 counties of Iowa, United States.

Crop Yield. Based on the best fitting Shukla model 2, the Wald F-test for fixed sources of variation showed statistical significance (\(p\)-value = 0.0246) for the drainage management main effect. This indicates that the CD management resulted in a statistically higher crop yield than the FD management. The drainage management and crop interaction was not significant (\(p\)-value = 0.3296), implying that the drainage management factor had the same yield-increasing effect for all levels of the crop factor.

Least square means of drainage managements calculated from the parameter estimates based on the best fitting model are summarized in table 6. Controlled drainage increased corn, popcorn, and soybean yield by 3.3%, 3.1%, and 2.1%, respectively, relative to FD management. Controlled drainage likely helps retain water in the soil profile for plant growth, which tends to lead to greater crop yield. Therefore, it can be concluded that CD can significantly increase crop yield in the target region of northwest Ohio.

Nistor and Lowenberg-DeBoer (2007) conducted an economic analysis to evaluate the profitability of CD in the midwestern United States. They concluded that a minimum yield benefit of 2% with subsidy and 4% without subsidy is sufficient to provide enough profit to justify implementing CD compared with conventional FD. Provided that the CD practice is cost-shared, the MET
Table 5
Parameter estimates based on different stability models.

<table>
<thead>
<tr>
<th>Drainage management</th>
<th>Compound symmetry (model 1)</th>
<th>Shukla (model 2)</th>
<th>Two-way extension of Shukla (model 4)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Corn</td>
<td>Popcorn</td>
<td>Soybean</td>
</tr>
<tr>
<td>Controlled Drainage</td>
<td>2.4144</td>
<td>0.1122</td>
<td>0.0280</td>
</tr>
<tr>
<td>Free drainage</td>
<td>2.4144</td>
<td>0.1122</td>
<td>0.0280</td>
</tr>
</tbody>
</table>

Table 6
Least square means of drainage managements based on the Shukla model 2 with standard error.

<table>
<thead>
<tr>
<th>Drainage management</th>
<th>Corn (Mg ha$^{-1}$)</th>
<th>Popcorn (Mg ha$^{-1}$)</th>
<th>Soybean (Mg ha$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Controlled drainage</td>
<td>11.74 (0.5519)</td>
<td>5.37 (0.8855)</td>
<td>3.39 (0.4410)</td>
</tr>
<tr>
<td>Free drainage</td>
<td>11.37 (0.5519)</td>
<td>5.21 (0.8855)</td>
<td>3.32 (0.4410)</td>
</tr>
</tbody>
</table>

reveals that CD provides greater profit to farmers in northwest Ohio by increasing corn, popcorn, and soybean yield by 3.3%, 3.1%, and 2.1%, respectively. The water conservation and quality benefits of CD has been well documented (Drury et al. 2009; Ramoska et al. 2011; Smith and Killman 2011; Fang et al. 2012). Thus, CD has the potential to provide greater profit to farmers in northwest Ohio while maintaining sound conservation practices.

Area of Influence. Similar to the results in the previous section, the Shukla model 2 was the best fitting model. The Wald-type F-test provided even stronger evidence of statistical significance ($p$-value = 0.0166) for the drainage management main effect compared to the whole field yield where a $p$-value of 0.0246 was observed. Least square means of drainage managements for popcorn did not change since the zone of influence for the environments with popcorn extended over the entire CD zone. Least square means of CD and FD for corn were 11.87 and 11.20 Mg ha$^{-1}$ (189.2 and 178.4 bu ac$^{-1}$) and for soybean were 3.48 and 3.36 Mg ha$^{-1}$ (51.7 and 49.9 bu ac$^{-1}$), respectively. This turns out to be a greater corn and soybean yield advantage of 6% and 3.5% compared to FD. The small area impacted by CD suggests that these sites need multiple control structures in order to increase the area of the fields influenced by CD. Consequently, fields with a greater slope need more investment in conservation practices.

Water Level. The number of hours the water table was within 1.3 m (4.3 ft) of the soil surface is illustrated in figure 4. Compared with FD, the total duration that the water table was within 1.3 m (4.3 ft) was longer for CD in all available environments. The relatively long-lasting higher water table could induce greater uptake of water by the plant roots. Therefore, we would expect greater crop yield under CD compared to FD.

Summary and Conclusions
In order for farmers to adopt CD, knowledge of its mean yield performance as well as its yield stability across different environments is essential. The implementation of CD in northwest Ohio significantly improved crop yield based on a mixed model analysis of 23 environments. As a result, corn, popcorn, and soybean yields were increased by 3.3%, 3.1%, and 2.1%, respectively. This study demonstrated that mixed model analysis is a suitable method of analyzing MET data to determine the regional performance of farming practices (e.g., drainage).

The area of influence analysis indicated a CD yield advantage of 6% and 3.5% for corn and soybean, respectively. The greater yield advantage from this method compared to the whole field analysis indicated that CD had the most profound impact in the area of influence. Therefore, CD is most suitable for relatively flat fields where the area of influence covers the entire field. This suggests that this practice could generate more profit than FD for relatively flat fields. The water table of CD was within 1.3 m (4.3 ft) of the soil surface for a longer period of the growing season than for FD, which is an indication of a raised water table in the field resulting in an increased crop yield.

The stability analysis based on the limited number of environments suggested that drainage managements were not different in yield stability. Nonetheless, a larger number of environments are needed to make a more precise assessment of yield stability. This study is expected to continue for several more years in which more environments will be obtained and analyzed to provide a more extensive understanding of the effect of CD on crop yield and stability.

In conclusion, this study demonstrated that CD provides a yield advantage for corn, popcorn, and soybean over conventional FD across multiple environments in northwest Ohio. The yield advantage of CD can provide financial incentive for farmers to adopt this practice, which also provides well-documented water conservation and quality benefits.

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