Vadose Zone Journal

Climate Variability and Drain Spacing Influence on Drainage Water Management System Operation

Srinivasulu Ale,* Laura C. Bowling, Jane R. Frankenberger, Sylvie M. Brouder, and Eileen J. Kladivko

The effects of climate variability, drain spacing, and growing season operational strategy on annual drain flow and crop yield were studied for a hypothetical drainage water management (DWM) system at Purdue University's Water Quality Field Station using the DRAINMOD model. Drainage water management showed potential for reducing annual average (1915–2006) drain flow from all drain spacings (10–35 m) regardless of the growing season operational strategy, with reductions varying between 52 and 55% for the drain spacings considered. Approximately 81 to 99% of the annual drain flow reduction occurred during the non-growing season, depending on the operational strategy. Fixed DWM operational strategies led to an increase in mean predicted yield for narrower spacings compared with conventional drainage systems. Maximum yield was achieved with no control for drain spacings wider than 20 m in 50% of the years. Overall, the height of control had more influence on relative yield than the date of initiation of control. The greatest positive impacts of DWM on relative yield (1.2%) occurred in cool, dry years, while the greatest average negative impacts (−0.2%) occurred in cool, wet years. On average, with the best-case operation selected for annual weather conditions, DWM increased relative yield by approximately 0.8, 0.4, and 0.2% for the 10-, 20-, and 30-m drain spacing, respectively. Accumulated growing degree days and antecedent precipitation index show promise for identifying appropriate operational strategies for DWM.

Abbreviations: API, antecedent precipitation index; DAP, days after planting; DWM, drainage water management; GDD, growing degree days; WQFS, Water Quality Field Station.

Artificial drainage is an important water management practice in the midwestern United States to remove excess water from poorly drained areas and to provide trafficable conditions for agricultural production. About 30% of the total land area and 50% of the crop land in Indiana is subsurface drained (Economic Research Service, 1987). There are growing concerns about the potential negative environmental impacts of subsurface drainage on the water quality of receiving water bodies and the hydrology of watersheds. Subsurface drains act as conduits for the movement of NO_3 and other nutrients and rapidly deliver them to surface water. Among several ways to reduce nonpoint-source pollution from subsurface drains, DWM, also known as controlled drainage, has been shown to reduce drainage outflow and NO_3 loading during certain times of the year (Evans et al., 1995; Lalonde et al., 1996; Fausey, 2004). In addition, DWM may increase crop yields in some years due to increased water conservation (Wesström and Messing, 2007). A DWM system consists of installing a water table control structure at the outlet of the subsurface drainage system, with which the outlet elevation can be managed at different times of the year (Frankenberger et al., 2006).

In the North American Corn Belt, annual drain flows vary widely, ranging between 0 and 40% of precipitation (Kladivko et al., 2001; Ruark et al., 2008). The drain flow volume is lower in drier years and also tends to be a lower percentage of total precipitation in these years (Kladivko et al., 2004). The horizontal spacing between parallel drains exerts a fundamental control on the drainage volume. Kladivko et al. (2004) found in a field study based in southeast Indiana that both drain flow and NO_3–N losses are greater per unit area for narrower drain spacings. Similarly, annual drain flow increased from 12 to 15 to 21% of annual precipitation as the drain spacing decreased from 20 to 10 to 5 m. Wiskow and van der Ploeg (2003) demonstrated with a two-dimensional drainage model that drain discharge is inversely and nonlinearly related to drain spacing across a range of spacings from 5 to 50 m. Nitrate concentrations apparently do not vary significantly with drain spacing (Kladivko et al., 2004), so it would seem that the greatest potential for drainage reduction, and therefore NO_3 load reduction, through DWM is on sites with narrower drain spacings.

Several field and modeling studies have demonstrated the potential of DWM for reductions in drain flow and thereby the NO_3 load (Kalita and Kanwar, 1993; Drury et al., 1996; Lalonde

S. Ale, L.C. Bowling, S.M. Brouder, and E.J. Kladivko, Dep. of Agronomy, 915 W. State St., Purdue Univ., West Lafayette, IN 47907-2054; and J.R. Frankenberger, Dep. of Agricultural and Biological Engineering, 225 S. University St., Purdue Univ., West Lafayette, IN 47907-2093. *Corresponding author (srinu@purdue.edu).

Vadose Zone J. 9:43–52
doi:10.2136/vzj2008.0170
Received 22 Nov. 2008.
Published online 11 Jan. 2010.

et al., 1996; Fausey et al., 2004; Singh et al., 2007; Ale et al., 2009). Interannual climate variability influences the need for drainage, as well as the need for water conservation later in the growing season. The potential for a positive influence on crop yields has been generally assumed (Frankenberger et al., 2006) based on limited field studies (Wesström and Messing, 2007) and modeling studies (Thorp et al., 2008). Recent simulation studies show that both the magnitude and direction of yield impacts vary from year to year based on the drainage system design and general weather patterns experienced. Singh et al. (2007) used the DRAINMOD model to predict the long-term effects of DWM on subsurface drainage, surface runoff, and crop production in Iowa. They simulated a Webster soil (a fine-loamy, mixed, superactive, mesic Typic Endoaquoll) in a continuous corn (*Zea mays* L.) rotation system with a drain depth of 1.20 m for 60 yr (1945–2004). The outlet control for DWM was maintained at 0.6 m below the soil surface during summer (June–August) and winter (November–March). Their analysis indicated a 9 to 18% reduction in average subsurface drainage outflow (statistically significant at the 95% level) and a slight reduction in average relative yield (statistically not significant) due to increased excess water stress under DWM compared with free drainage.

In another simulation study at Nashua, IA, using the RZWQM model, Ma et al. (2007) predicted a 30% reduction in average annual drain flow with DWM compared with free drainage when the drain depth was 1.20 m. The predicted crop yield was not affected by DWM in these simulations. The simulated DWM operational strategy maintained an outlet control at 0.6 m below the soil surface during the summer (10 June–10 September) and 0.3 m below the surface during the winter (1 November–15 March).

The performance of conventional and DWM practices for 25 yr (1966–1990) at 48 locations across the midwestern United States was simulated by Thorp et al. (2008) using the RZWQM-DSSAT hybrid model, which includes a dynamic crop growth component. They reported an average annual drain flow reduction of 53% (within a range of 35 to 68%) with DWM compared with conventional drainage. For DWM simulations, outlet control was maintained at 0.6 m below the surface during the growing season (from 4 wk after planting to 2 wk before harvest) and 0.3 m below the surface during the fall and winter seasons (from 1 wk after harvest to 3 wk before planting). The predicted average changes in corn and soybean [*Glycine max* (L.) Merr.] yield under DWM across the region were 3% (with in a range of −0.2 to 12%) and 4% (within a range of 0.3 to 10%), respectively. They noted that crop yield predictions may be overestimated during wet conditions due to the lack of representation of yield loss due to anaerobic conditions and the inability to simulate root depths in response to saturated soil conditions. These studies were based on a fixed DWM operational strategy and did not evaluate the effects of various DWM operational strategies. Furthermore, the effect of climate variables on annual drain flow reduction and risk to crop yield was not studied.

The identification of optimal DWM operational strategies that minimize drain flow and maximize crop yield under varying soil and climatic conditions can provide guidance during early adoption of the practice. The operational and management choices include the height of control and the dates of initiation and withdrawal of control during the cropping season and the non-growing season. In the Midwest, there is insufficient experimental data to make recommendations about the operation of DWM systems. Ale et al. (2009) examined the relative impacts of deficit water and excess water stress during a period of 15 yr (1991–2005) using the DRAINMOD model and identified an operational strategy for Drummer soil (a fine-silty, mixed, superactive, mesic Typic Endoaquoll) for the 10-m drain spacing plots at Purdue University's Water Quality Field Station (WQFS). For the hypothetical DWM situation at the WQFS, they identified the preferable dates of raising and lowering the outlet during the crop period as 10 d after planting and about 4 to 6 wk before crop maturity, and the height of control as 50 cm above the drain (40 cm from the surface). The crop yield and drain flow were not sensitive to the date of lowering the outlet toward the end of the crop season. The 10-m drain spacing at the WQFS, however, is a closer spacing than is typical in Indiana and the analysis based on 15 yr of weather record might not have covered the full range of variability in wet and dry stresses that occur. The purpose of this study was to extend the analysis of Ale et al. (2009) to examine the sensitivity of DWM operational strategies for different drain spacings (10–35 m) during a longer record (1915–2006) and to explore the potential for a dynamic operational strategy to enhance crop yield in some years while minimizing the average annual drain flow and crop risk in all years.

Materials and Methods

Study Site

Purdue University's WQFS is located in the Tipton till plain region of west-central Indiana. It was established in 1992 to study the impacts of drain spacing and cropping system treatments on water quality. Soils at the WQFS are predominantly Drummer silty clay loam (Soil Conservation Service, 1998; Hofmann et al., 2004). The Drummer soils are distributed across northern and central Illinois, northwestern Indiana, and southeastern Wisconsin. Drummer soil represents approximately 17,400 ha (13.3%) of the total land area in Indiana (Hofmann, 2002). They are the most productive soils in the state and corn and soybean are the principal crops grown in these soils. In general, the Drummer series consists of very deep, poorly drained soils formed in loess or other silty material on nearly level or depressional parts of outwash plains, stream terraces, and till plains (Soil Survey Staff, 2008). Slope ranges from 0 to 2% and hence many of these soils are suitable for DWM. At the WQFS, the glacial till found at a depth of approximately 147 cm acts as a restrictive layer (Hofmann, 2002). Forty-eight treatment plots (12 cropping system treatments replicated four times) were established in a randomized complete block design. Each treatment plot measures 48.5 by 10 m and contains a drainage lysimeter that drains an area of 24 by 10 m. The perforated drain pipe was installed in the center of each lysimeter at a depth of 90 cm. In addition to the 48 drainage lysimeter plots, six drain spacing plots are laid out at the WQFS on three standard spacings of 10, 20, and 30 m to facilitate the scaling of lysimeter data to match standard agricultural drainage practices (Hofmann et al., 2004). Further details about the design and monitoring of the drainage system at WQFS can be found in Ale et al. (2009). Ale et al. (2009) used drain flow data from the continuous corn treatment with a urea–NH_4NO_3 application rate of 224 kg N ha^{-1}, with insecticide application at planting and a broadcast application of herbicide after planting.

DRAINMOD

The DRAINMOD model is a process-based, field-scale model that simulates the hydrology of poorly drained, high-water-table soils on an hourly basis for long periods of climatological record (Skaggs, 1978). The model is based on a water balance in the soil profile for a thin section of soil of unit surface area located midway between adjacent drains and extending from a restrictive layer to the surface. The model predicts the effects of drainage and related water table management practices (DWM and subirrigation) on the hydrology and water quality of agricultural lands and crop yields. Using the controlled drainage mode, it is possible to simulate the long-term impacts of DWM on hydrology and relative crop yield. The recent versions of DRAINMOD also include routines for soil temperature modeling, and consider freezing and thawing effects on drainage processes (Luo et al., 2000, 2001). A detailed description of the model can be found in Skaggs (1978, 1991).

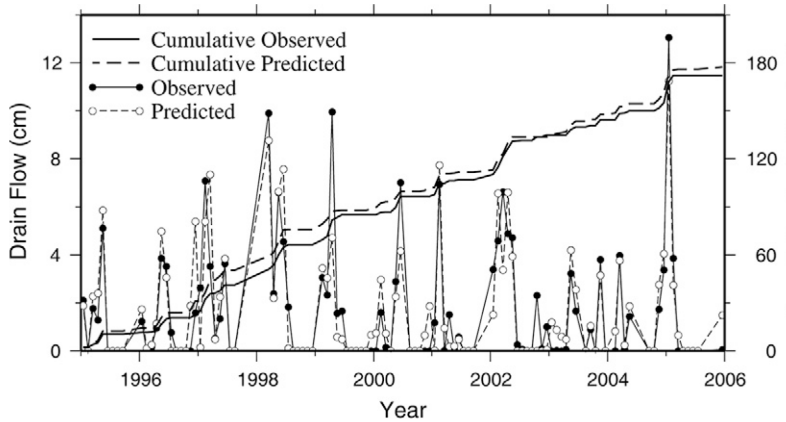

Fig. 1. Predicted and observed monthly drain flows for continuous corn treatment plots at Purdue University's Water Quality Field Station. The observed drain flows represent the average of four replicates. The months in which whole or partial observed drain flow events are missing (due to either flooding or equipment malfunction), are excluded from comparison. (Based on the results presented in Ale et al., 2009).

The DRAINMOD model simulates crop growth through a simplified yield reduction approach accounting for delayed planting, excess water, and drought stress during the crop growth period and does not simulate the effects of the fertilizer application rate on crop yield. The relative yield (RY) is the estimated ratio of the actual crop yield to the potential, or maximum attainable, yield. The RY, expressed as a percentage, is computed in DRAINMOD using the following equation (Skaggs, 1990):

$$RY = RYp \times RYw \times RYd \qquad [1]$$

where RYp is the relative yield that would be obtained if only reduction due to planting date delay is considered, RYw is the relative yield if only reductions due to excessive soil water conditions are considered, and RYd is the relative crop yield if the only reductions are due to deficit soil water. All of the relative yields are calculated as a linear (or piecewise linear) function of an independent variable describing the magnitude of the stress, with a *y* intercept of relative yield. Further details about RY estimation can be found in Skaggs (1991). Ale et al. (2009) previously evaluated the yield–stress relationships for corn at the WQFS. The potential yield was assumed to be the highest observed corn yield among all replications of continuous corn treatment at WQFS between 1997 and 2005.

Model Implementation

Ale et al. (2009) calibrated and validated the DRAINMOD model for the WQFS site based on observed drain flow data from the four replicates of continuous corn treatment plots, with a 10-m drain spacing, for the period from 1995 to 2005 (Fig. 1). The DRAINMOD model inputs used in this study are the same as those used by Ale et al. (2009) for soil (soil moisture characteristics), crop (crop calendar and trafficability data), and drainage system (drain depth). The daily precipitation and daily maximum and minimum temperature data for the period from 1915 to 2006 were taken from a gridded data set based on the observed daily precipitation and minimum and maximum temperature from National Climatic Data Center stations, interpolated to the nearest one-eighth degree of latitude and longitude (Sinha, 2008). The interpolated data are corrected using the methodology of Hamlet and Lettenmaier (2005) to account for temporal inconsistencies in the number of gauges in the record.

Ale et al. (2009) found that DRAINMOD predicted the drain flows reasonably well with good monthly statistics: Nash–Sutcliff efficiency of 0.70 and 0.85; index of agreement of 0.91 and 0.96; and Percent Error (PE) of 5.6 and 0% for the calibration and validation periods, respectively. The average absolute PE in relative yield prediction was 12.4%, ranging from −25.7 to 30% (Ale et al., 2009). The calibrated model of Ale et al. (2009) is used in this study with a longer period of weather record (1915–2006) and for multiple drain spacings (10–35 m).

Climate Variability Classification

To study the influence of climate variability, the 92-yr record was divided into wet, dry, and intermediate years based on the growing season (1 May–30 September) precipitation. Dry years are those years with the growing season precipitation (GSP) less than the 33rd percentile GSP (42 cm) and the wet years are those years with the GSP greater than the 67th percentile GSP (50 cm). The remaining years are the intermediate years. According to Neild and Newman (1990), 45 to 50 cm of moisture is required during the growing season to obtain high corn yields, which corresponds well with the above percentiles.

The period of record was also divided into cool, intermediate, and warm years based on the cumulative growing degree days (GDD) between 1 May and 30 September. Historically, the number of days from planting to harvest has been used to classify the maturity of corn hybrids. In recent years, commercial corn hybrid maturity is often determined by GDD (Neild and Newman, 1990). The GDD are calculated as the difference between the daily average temperature and the base temperature. The daily values are summed to get the cumulative GDD at various stages of crop growth. The base temperature is considered to be the minimum temperature required for crop growth and is usually set to 10°C, as it was here. Warm years are classified here as those years with cumulative GDD (calculated from 1 May to 30 September) greater than or equal to the 67th percentile GDD (1632°C d); cool years are those with the GDD less than the 33rd percentile (1456°C d). All other years were classified as intermediate years. The average midseason commercial corn hybrid in the central Corn Belt requires about 130 d from planting to maturity, or 1482°C d GDD (Neild and Newman, 1990).

In addition to GDD, the antecedent precipitation index (API) was estimated to study the influence of spring season moisture on the operation of DWM systems. Together, the GDD and API were used as indicators to decide the date of initiation of control under varied climatic conditions. The API is defined as a weighted summation of daily precipitation amounts and is used as an index of soil moisture (Betson et al., 1969). The API on the tth day is calculated as

$$\mathrm{API}_t = K_t \mathrm{API}_{t-1} + P_t \quad [2]$$

where K_t is the recession coefficient and P_t is the precipitation occurring on the tth day. The API was calculated daily, continuously from the first day of simulation (1 Jan. 1915), for which the API was assumed to be zero. The recession coefficient represents the "memory" of a particular watershed by decaying the effect of accumulated rainfall at each time step. The recession coefficient was calculated on a daily basis, using the method of Choudhury and Blanchard (1983):

$$K_t = \exp\left[\frac{-E_\mathrm{p}}{z\left(\theta_\mathrm{fc} - \theta_\mathrm{w}\right)}\right] \quad [3]$$

where E_p is the daily potential evaporation (mm), z is the maximum soil depth from which evaporation can occur (mm), θ_fc is the volumetric water content at field capacity, and θ_w is the volumetric water content at the wilting point. The depth of plant-available water, $z(\theta_\mathrm{fc} - \theta_\mathrm{w})$, was set to 6.55 cm to correspond to the inputs used for the DRAINMOD model for the WQFS. Daily potential evaporation was calculated using the Thornthwaite equation with published monthly correction factors for Indianapolis, IN (Wang et al., 2006).

Scenarios Simulated

As a baseline scenario, the model was used to predict the crop yield and hydrology for conventional drainage with multiple drain spacings ranging from 10 to 35 m with an increment of 5 m. Several hypothetical DWM simulations were subsequently made by varying the drain spacing, the date of initiation of control in the spring, and the height of the growing season control, as follows: (i) DWM for multiple drain spacings (10–35 m) with the height of control above the drain during the crop season fixed at 30 cm (60 cm from the surface) and varying the date of raising the outlet from 0 (date of planting) to 40 d after planting (DAP) with an increment of 5 d; (ii) DWM for multiple drain spacings (10–35 m) with the date of control fixed at 20 DAP and varying the height of control during the crop season from 10 to 90 cm (80 to 0 cm from the surface) with an increment of 20 cm; and (iii) DWM for the 20-m drain spacing by simultaneously varying the date of raising the outlet from 0 to 40 DAP with an increment of 5 d and the height of control during the crop season from 10 to 90 cm with an increment of 20 cm.

Ale et al. (2009) recommended a growing-season control height of 50 cm above the drain initiated 10 DAP for the 10-m drainage lysimeter plots at the WQFS. Based on preliminary analysis for other spacings, as discussed later, this level of control appeared excessively wet, leading to the choice of a fixed control height at 30 cm in the first scenarios and a control initiation 20 DAP in the second scenarios.

For all of the alternative scenarios, the winter period control was set from 1 November to 31 March. This is justifiable because the spring field operations in Indiana typically begin in the second week of April and harvesting in the fall typically continues into the third week of October. A control height of 90 cm above the subsurface drain (setting the outlet at the soil surface) was maintained during the winter period. The date of lowering the outlet toward the end of the crop season, which was found to be a less sensitive parameter, was also fixed at 85 DAP, as recommended by Ale et al. (2009). For all the DWM simulations, it was assumed that there are no post-planting operations during the growing season because there is no provision in the model to include trafficability parameters during the growing season. This is in agreement with the medium- and high-fertilizer treatments at WQFS, in which fertilizer is applied as a preplant application. The effects of varying the drain spacing, the date of initiation of control, and the height of control during the crop season on the predicted relative yield and hydrology were examined.

Results and Discussion

Conventional Drainage System

The simulated average (1915–2006) annual values of water balance variables for multiple drain spacings are given in Table 1. Between 1915 and 2006, the annual precipitation varied from 61.4 cm (in 1956) to 125.4 cm (in 1998), with an average of 91.9 cm (Table 1). The growing season (1 May–30 September) precipitation varied from 24.8 cm (1930) to 73.7 cm (2003), with an average of 46.8 cm. As the drain spacing was increased from 10 to 35 m, the predicted average annual drain flow decreased from 21.2 to 12.1 cm and surface runoff increased from 2.1 to 3.9 cm. As the spacing increased, wet stress increased and dry stress decreased, with corresponding impacts on the wet-stress related yield (RYw) and dry-stress related yield (RYd) (Fig. 2a). The average (1915–2006) predicted overall relative yield (RY) under conventional drainage is maximized at about 20-m drain spacing (Fig. 2a), which is also the typical drain spacing in Indiana. Hofmann et al. (2004) also found that the observed corn yield was the maximum for 20-m plots, compared with 10- and 30-m plots at the WQFS.

Impact of Drain Spacing on Operation of Drainage Water Management System

Figures 2b and 2c explore the influence of DWM on relative yield by showing the RY ratio (RY under DWM vs. conventional RY) for different drain spacings and dates of control initiation for

Table 1. Predicted average annual water balance components of Drummer soil under a conventional drainage system at drain spacings of 10 to 35 m for 92 yr (1915–2006) based on measured average annual precipitation of 91.9 cm and average growing season precipitation of 46.8 cm.

Parameter	10 m	15 m	20 m	25 m	30 m	35 m
			cm			
Evapotranspiration	64.0	64.7	65.2	65.6	65.9	66.1
Subsurface drainage	21.2	19.1	17.1	15.2	13.6	12.1
Surface runoff	2.1	2.5	2.8	3.2	3.5	3.9
Vertical seepage	4.6	6.3	6.8	7.9	8.9	9.7

a fixed control height of 50 cm (as recommended for the narrower spacings by Ale et al., 2009) and 30 cm. When the outlet was raised between 0 and 20 DAP with the control height fixed at 50 cm, the long-term average (1915–2006) RY ratio was positive ($\geq$1.0) for only the 10-m spacing (Fig. 2b). Raising the outlet to a height of 50 cm within 20 DAP is therefore acceptable for the 10-m drain spacing and is in agreement with the recommendations of Ale et al. (2009) based on the analysis for 10-m spacing during a 15-yr period (1991–2005). The RY ratio for the other simulated drain spacings indicates that this strategy is more likely to decrease the average crop yield due to increased wet stress (Fig. 2b). When the height of control was changed to 30 cm, the effect of increased wet stress with DWM was decreased, as indicated by the variation in RY across a shorter range compared with the variation with a 50-cm control height (Fig. 2c vs. 2b). Furthermore, the average RY ratio was $\geq$1.0 for drain spacings <20 m (except for the 40 DAP scenario) (Fig. 2c). On average, DWM was therefore found to have a positive influence on RY only for narrower spacings (<20 m) because the increased drainage intensity with narrower spacings offsets the excess wet stress caused by the DWM, and the DWM increases water availability to crops in some years. The negative effect of DWM on crop yield for wider spacings is in agreement with the study by Singh et al. (2007), who predicted a slight reduction in crop yield with DWM for the conditions in Iowa. In contrast, Ma et al. (2007) predicted no effect of DWM on crop yield, and Thorp et al. (2008) predicted a slight increase in crop yield with DWM (both with a drain spacing of ~30 m). Thorp et al. (2008) acknowledged, however, that the crop yield predictions in their study might have been overestimated during wet conditions.

In general, the height of control had more influence on RY (RY ratio varied between 1.00 and 0.96) than the date of initiation of control (RY ratio varied between 1.01 and 0.99) for multiple drain spacings (Fig. 2c and 2d). The wider spacings are more sensitive to the date of initiation of the control than the narrower spacings (Fig. 2c) and hence it is preferable to initiate the control later in the season as the drain spacing increases. The average (1915–2006) RY is more sensitive to control heights >30 cm due to an increase in excess water stress (Fig. 2d). When the outlet was raised to a height of 30 cm above the drain (60 cm from the surface) 20 d after planting, the average change in RY due to DWM for the 10-, 15-, 20-, 25-, 30-, and 35-m drain spacings was 0.2, 0.1, –0.2, –0.5, –0.6, and –0.6%, respectively, compared with conventional drainage. Although the average simulated yield is maximized for all spacings with the minimum amount of control (10-cm control height) (Fig. 2d), a fixed control height of 30 cm appears to be reasonable for drain spacings $\geq$20 m to maximize the drainage reduction with minimum yield impact. This control height was used for further sensitivity analysis.

The RY presented in Fig. 2 under various DWM operational strategies is the average RY for the 1915 to 2006 period, indicating that in some years there could be an increase in RY and in some years there could be a reduction in RY. The years in which management decisions impacted yield were studied in more detail to identify preferable DWM operational strategies for different drain spacings (Fig. 3). As drain spacing increased, the preferred date to raise the outlet moved later in some years due to a general increase in excess water stress with larger spacings (Fig. 3a). The interquartile range (between the 25th and 75th percentiles)

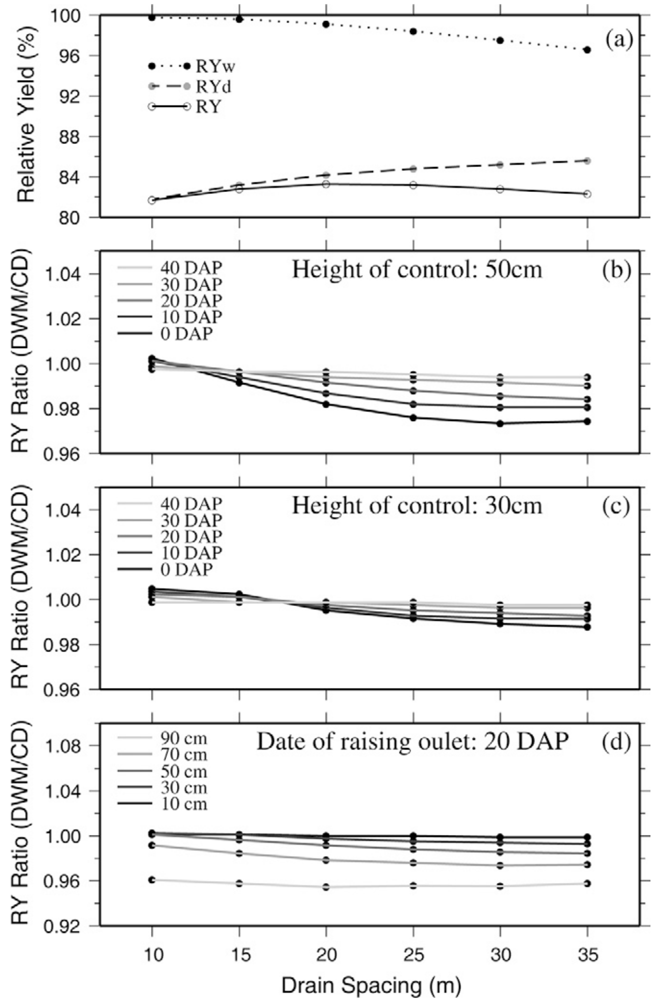

Fig. 2. (a) Mean (1915–2006) simulated relative yield (RY) with respect to drain spacing for conventional drainage (CD), also showing the trade-off between wet-stress related yield (RYw) and dry-stress related yield (RYd); and the effect of drain spacing on the ratio of drainage water management (DWM) RY and conventional RY for (b) DWM for five (out of nine) different dates of raising the outlet to a height of 50 cm above the drain, (c) DWM for five (out of nine) different dates of raising the outlet to a height of 30 cm above the drain, and (d) DWM for five different heights of control when the outlet is raised 20 d after planting (DAP).

of control initiation dates for maximum yield varied from 0 to 10 DAP for the 10-m drain spacing and from 0 to 30 DAP for the 35-m spacing. This is in agreement with the recommendations made by Ale et al. (2009) for the 10-m drain spacing. For smaller drain spacings, water drains out of the soil more rapidly and hence early initiation of control can improve moisture availability to plants and thereby increase the yield. The interquartile range of preferred heights of control varied from 0 (no control) to 50 cm for the narrowest spacing (10 m), to 0 to 10 cm for the wider spacings ($\geq$25 m) (Fig. 3b). For the narrow spacings, higher levels of control are needed to maintain soil moisture in some years. The median of the preferable dates of initiation of control (at 30-cm height) during the crop period to achieve maximum yield are therefore on the date of planting (0 DAP), 5 DAP, and 10 DAP for the 10-, 15- to 25-, and $\geq$30-m drain spacings (Fig. 3a). The median preferable height of control (when initiated 20

DAP) was 10 cm for drain spacings ≤20 m and no control for drain spacings wider than 20 m (Fig. 3b).

Impact of Preferable Operational Strategy on Yield

For the best-case operation of DWM in each year (the case in which the highest yield was predicted across all DAP simulations with a 30-cm height of control and all control height simulations with the outlet raised 20 DAP), the effect of DWM on RY was found to be negligible (–0.5 to 0.5%) in about 62 to 66 yr for all spacings (Fig. 4). On average, with "best-case" operation, DWM increased the RY by approximately 0.8, 0.4, and 0.2% for the 10-, 20-, and 30-m drain spacings, respectively. As the drain spacing increased, the number of years with negligible yield impact and the years with negative yield impact due to DWM also increased slightly. The highest yield increase of 8% was predicted for the 10-m drain spacing compared with a maximum increase of 4 and 3% RY for the 20- and 30-m drain spacings, respectively. Given that the fields with narrow spacing are expected to drain faster, they are drier on average and DWM has a greater capacity to increase the moisture availability to plants in dry years. In the model simulations presented in this study, the control is implemented with the set operational strategy for all years and simulations are made regardless of wetness conditions, which may cause significant yield reductions in some years. In reality, if the land is wet, the farmer may not start the control until the land is dry enough to implement DWM, and in wet years DWM may not be implemented during the growing season at all. Non-adoption of DWM during the growing season of those wet years in which RY was negatively influenced would further improve the overall yield benefits with DWM.

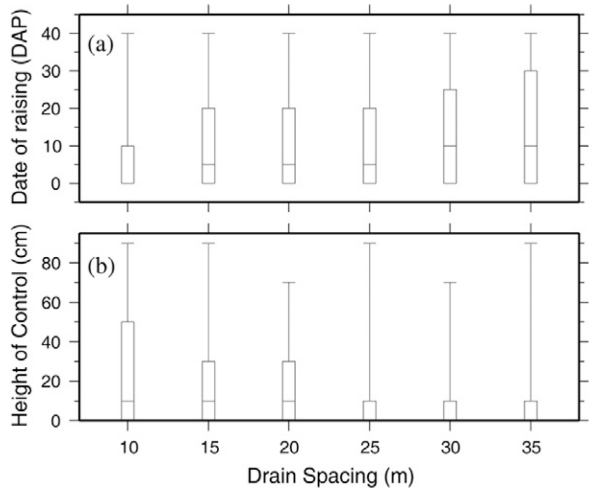

Fig. 3. The range of preferable (a) dates of initiation of control when the outlet was raised to a height of 30 cm, and (b) heights of control when the outlet was raised 20 d after planting (DAP) to maximize the relative yield with drainage water management for multiple drain spacings among the responsive years in which operational strategy impacted relative yield. The upper end of the top whisker, upper edge of the box, the line inside the box, and the bottom edge of the box in each box plot are the largest, upper quartile, median, and the lower quartile observations, respectively. The lower end of the whisker, which is the smallest observation, is the same as the lower quartile in all the cases and hence coincided with the bottom edge of the box.

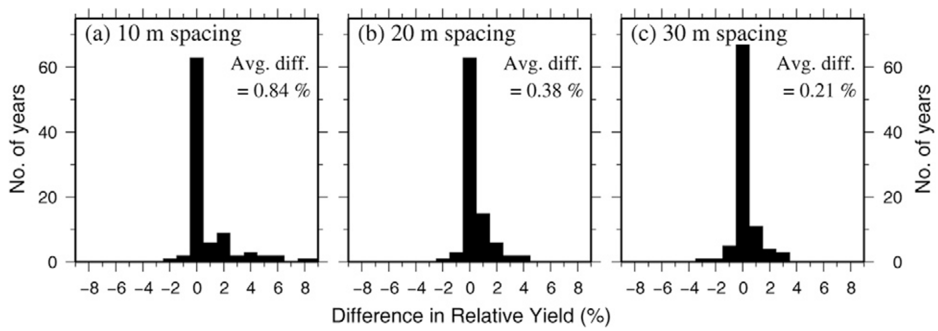

Fig. 4. Distribution of changes in relative yield (drainage water management [DWM] minus conventional) for the best-case operation of DWM in each year, for drain spacing of (a) 10, (b) 20, and (c) 30 m. The best-case operation is the operation in each year in which yield is maximized across all 14 scenarios: nine date-of-control-initiation simulations for the 30-cm control height and five control-height simulations with the outlet raised 20 d after planting.

Effect of Drain Spacing on Drain Flow Reduction with Drainage Water Management

Drainage water management results in a substantial reduction in drain flow (Fig. 5). As the drain spacing increased, the reduction in the absolute quantity of drain flow decreased. On average, a reduction in annual drain flow of 11.4 (52%), 9.4 (55%), and 7.5 cm (55%) was predicted with DWM relative to conventional drainage for 10-, 20-, and 30-m drain spacings, respectively. The highest annual reduction in drain flow was 24, 22, and 18 cm for the 10-, 20-, and 30-m drain spacings, respectively. This is the most significant benefit of DWM because reduction in drain flow reduces the NO_3 load to receiving streams and hence may lead to improvements in water quality. Wesström et al. (2001) reported that the total reductions in NO_3 losses (78 and 94%) with DWM were closely related to reduced drain flow rates (79 and 94%). Much of this drain flow reduction occurs during the non-growing season (Fig. 6).

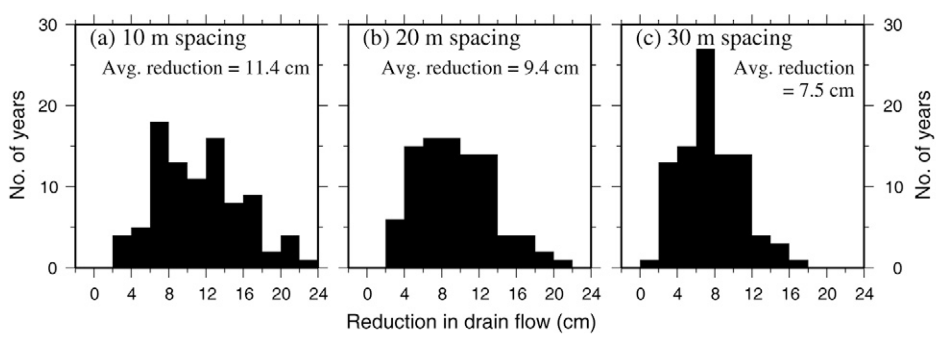

Fig. 5. Distribution of the reduction in drain flow (conventional minus drainage water management [DWM]) for the best-case operation of DWM in each year for drain spacing of (a) 10, (b) 20, and (c) 30 m. The best-case operation is the operation in each year in which yield is maximized across all 14 scenarios: nine date-of-control-initiation simulations for the 30-cm control height and five control-height simulations with the outlet raised 20 d after planting.

As the level of drainage water management decreased from the maximum simulated control (control height of 90 cm and raising the outlet on 0 DAP) to the minimum control (10-cm height and raising the outlet on 40 DAP), the pproportion of the annual drain flow reduction that occurred during the growing season varied from 19 to 1%. The variation in drain flow reduction during the growing season among the two intermediate operational strategies was only 4% (10 vs. 6% in the case of 50 cm at 10 DAP and 30 cm at 20 DAP operational strategies, respectively), however. The volume of drain flow reduction in the non-growing season was the same in each scenario because the operational strategy during the winter was unchanged. From the water quality point of view, adjusting the operational strategy during the growing season may therefore not have a substantial influence on annual reductions in the drain flow (and thereby the NO_3 load).

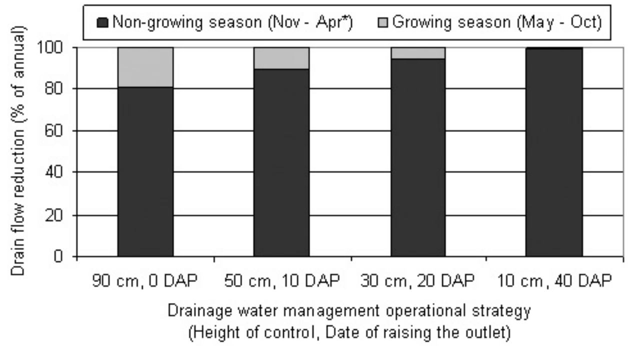

Fig. 6. Seasonal distribution of drain flow reduction for the 20-m drain spacing with the highest (90-cm height of control, raising the outlet 0 d after planting [DAP]), intermediate (50 cm, 10 DAP and 30 cm, 20 DAP) and the lowest (10 cm, 40 DAP) levels of drainage water management during the growing season. *The release of the winter control on 31 March caused an increase in drain flow in April and hence April was included in the non-growing-season control period for drain flow reduction computations.

Interaction of Height of Control and Date of Initiation of Control

The two-way interactions between the date of initiation of control and the height of control for the 20-m drain spacing on crop yield and hydrology are illustrated in Fig. 7. As the date of initiation of control was moved closer to the planting date and as the height of control was increased, the relative yield and average annual drain flow decreased, and the average annual seepage loss and surface runoff increased. As the height of control increased, yield was more sensitive to the date of raising the outlet (Fig. 7a). There was not much variation in the impact of the height of control on RY up to 50 cm of control, after which the RY decreased rapidly with the increase in the height of control (Fig. 7a). In general, the growing season strategies did not have a substantial effect on hydrologic variables (maximum differences of only 3, 2, and 1 cm in the cases of drain flow, seepage, and runoff, respectively) because much of the drain flow occurred in the non-growing season (Fig. 7b–7d). All heights of control showed some positive water conservation effect with a reduction in drain flows compared with conventional drainage (Fig. 7c). As the intensity of DWM increased, the drain flow reduced and seepage increased (Fig. 7b and 7c). Higher seepage could be due to the relatively high calibrated vertical conductivity of the restrictive layer (Ale et al., 2009). The variability in drain flow was higher than the variation in seepage among different combinations of dates of initiation of control and control heights, indicating that about 50% of the drain flow reduction went to vertical seepage (Fig. 7b and 7c). As the height of control increased and the date of initiation of control moved closer to the planting date, surface runoff increased slightly, with a total range of <0.5 cm (Fig. 7d). More variation in surface runoff was predicted for control heights $\geq$50 cm and initiation of control within 0 to 10 DAP.

Impact of Climate Variability on Operation of Drainage Water Management Systems

The results presented so far focus on long-term averages as a means to demonstrate the influence of a DWM operational strategy on relative yield and hydrology. Average results can mask the year-to-year variability in DWM impacts due to climate variability, which can be better shown through probability of non-exceedance plots (Fig. 8a and 8b). In about a quarter of the years, simulated relative yield reached 100% for all of the DWM scenarios, irrespective of the dates of raising the outlet and the heights of control, as shown for example for the 20-m drain spacing (Fig. 8a and 8b). A substantial effect of the date of raising the outlet on RY was seen in only a few years across the range of 90 to 95% RY (Fig. 8a).

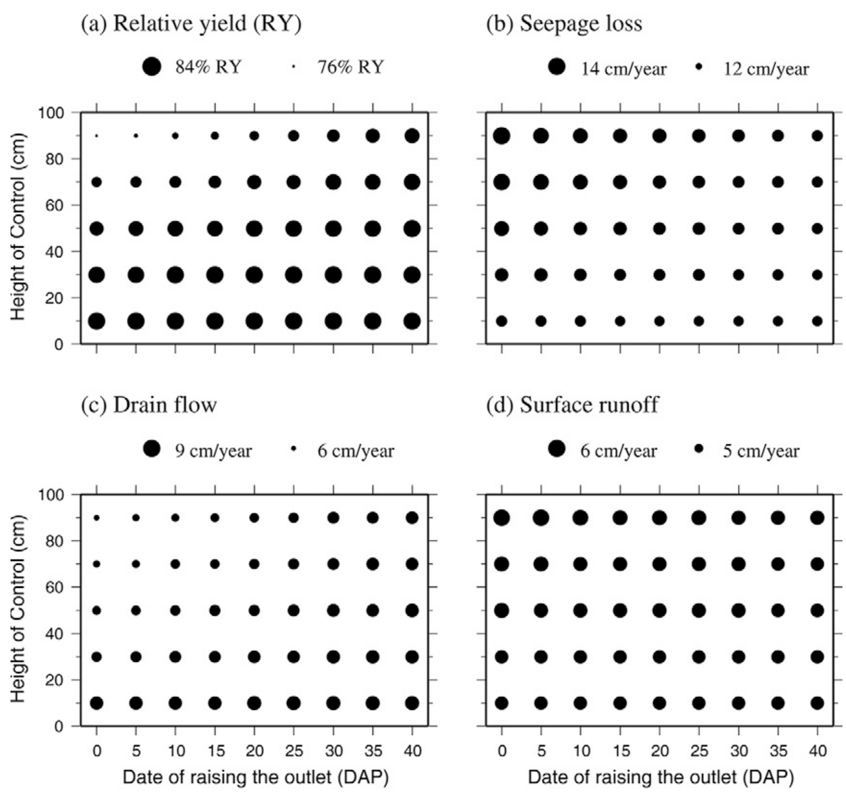

Fig. 7. Two-way interaction of the date of initiation of control and the height of control for the 20-m drain spacing, illustrating the relative impact on (a) relative yield, (b) average annual seepage loss, (c) average annual drain flow, and (d) average annual surface runoff.

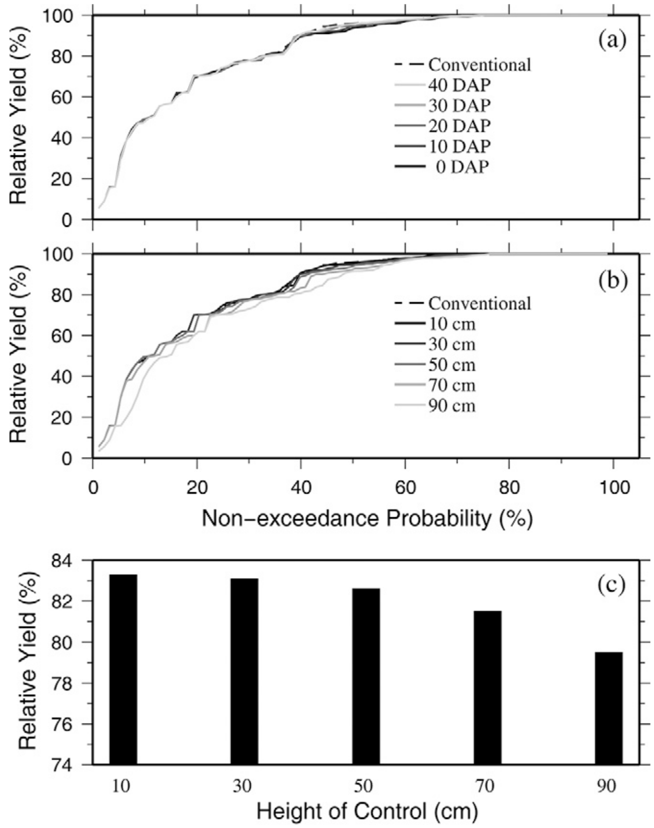

Fig. 8. Year-to-year variability (1915–2006) in drainage water management impacts on relative yield for the 20-m drain spacing for (a) multiple dates of raising the outlet when the height of control was 30 cm, and (b) multiple heights of control when the outlet was raised 20 d after planting (DAP); (c) the effect of the height of control on the average relative corn yield for the 20-m drain spacing among the years that were sensitive to the height of control when the outlet was raised 20 DAP.

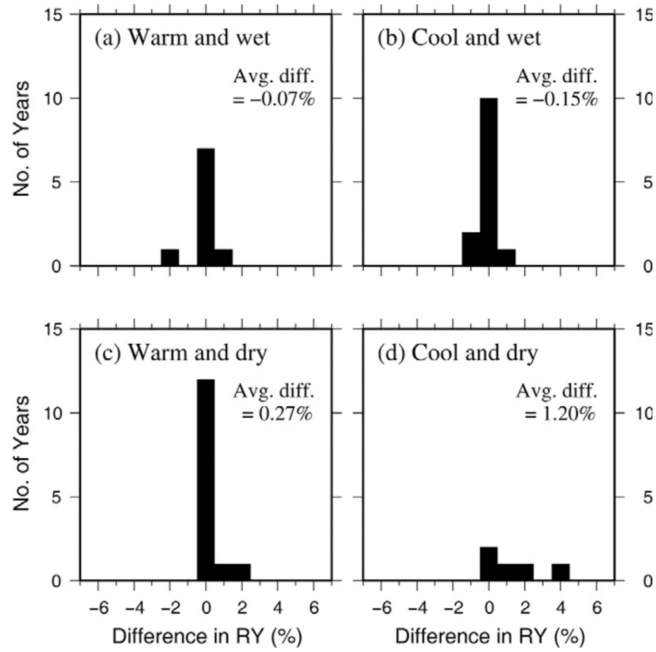

Fig. 9. Distribution of yield differences (drainage water management [DWM] minus conventional) for the best-case operation of DWM in each year for the 20-m spacing divided by the growing season climate variability: (a) warm and wet, (b) cool and wet, (c) warm and dry, and (d) cool and dry. The best-case operation is the operation in each year in which yield is maximized across all 14 scenarios: nine date-of-control-initiation simulations for the 30-cm control height and five control-height simulations with the outlet raised 20 d after planting.

The effect of height of control on RY was much more prominent in more years (approximately 67% of years) than the effect of the date of initiation of control (Fig. 8b). The years in which RY was not influenced by the height of control include about 8% of the years with low RY (≤40%), in which RY was impacted with the 90-cm control (complete lack of drainage) only and about 25% of the years in which the RY remained at 100%. Among the years in which RY was influenced, there was less stress on RY up to 30 cm of control height, and yield decreased slowly up to 50-cm control and rapidly thereafter (Fig. 8b and 8c).

The largest average yield increase under the best-case operation occurred under cool and dry growing season conditions for the 20-m drain spacing (Fig. 9). Positive impacts of DWM on RY were found in both cool, dry years (1.2% increase) and warm, dry years (0.3% increase), in which there are no negative yield impacts (Fig. 9c and 9d). The increased availability of water due to DWM in the dry years probably leads to the increased RY. Cooler climate in the dry years might have further improved the RY because of the reduced evapotranspiration requirement. The greatest negative effect was found in cool, wet years (0.2% reduction), in which there were the most individual years of negative yield impacts (Fig. 9b). In general, cool and wet climatic conditions are not desirable for crop production because these conditions cause excessive moisture stress, and DWM further enhances the wetness condition of the soil due to storage of excessive water in the soil profile. Cooler temperatures in these wet years further aggravate the problem due to less evapotranspiration.

Potential for a Dynamic Operational Strategy

Identification of drier and warmer years based on GDD and API and adjustment of operational strategies accordingly may lead to positive yield benefits with DWM. To explore the potential for developing such dynamic operational strategies, we studied the variation in GDD and API on the preferred dates of raising the outlet for multiple drain spacings when the outlet was raised to a height of 30 cm averaged across all years (1915–2006) (Fig. 10). The preferred date is the date on which yield is maximized when considering the nine simulated DAP scenarios, including only those years in which yield varied with DAP. In general, outlet control for smaller drain spacings can be initiated earlier (with lower cumulative GDD) and under wetter antecedent conditions (higher API; Fig. 10). Because the narrower drains remove excess water so much more quickly, less evaporative drying is needed to remove the risk of excess water stress. This suggests that for a 10-m spacing, outlet control could begin once cumulative GDD is greater than 239°C d and API is <132 mm, while for a 20-m drain spacing the cumulative GDD should exceed 281°C d, with an API <127 mm. It is not clear why the mean API increases for 25- and 35-m spacing. It could indicate that if outlet control begins late enough in the growing season when evaporative demand is higher, then the simulated yield will be less sensitive to the antecedent soil moisture content, but more data is needed to evaluate this interpretation. Overall, the time until initiation of control should therefore increase with increased drain spacing. Presenting the API and GDD values for each spacing provides an index for deciding the date of raising the outlet during the crop growing season. Further research is needed to determine to what degree this could be implemented based on real-time weather information, and the magnitude of potential benefits.

Conclusions

The influence of climate variability during 92 yr (1915–2006), drain spacing (within a range of 10 to 35 m), and growing season operational strategy on annual performance of a hypothetical DWM system on Drummer soil at Purdue University's WQFS was studied using the DRAINMOD model. The effects of the date of initiation of the control and height of control during the crop season on corn relative yield and hydrology for multiple drain spacings were analyzed. The climatic record was divided into dry vs. wet based on the growing season precipitation, and warm vs. cool years based on GDD. This analysis suggests the following conclusions:

1. Drainage water management showed great potential for reducing annual drain flow. The long-term average (1915–2006) annual drain flow reduction due to DWM varied between 52 and 55% for all drain spacings and operational strategies considered. This would also be the probable reduction in NO_3 loads to receiving streams. Depending on the growing season operational strategy, about 81 to 99% of the annual drain flow reduction occurred during the non-growing season.
2. On average, the DWM operational strategies led to an increase in the mean expected yield for narrower spacings and a decrease in the mean expected yield for wider spacings compared with conventional drainage systems. The effect of DWM on RY was found to be negligible (−0.5 to 0.5%) in about two-thirds of the years for all spacings, however.
3. For wider drain spacings, the operational strategy should reflect a decrease in the magnitude of control (later date of raising the outlet or a lower height of control). The median of the preferable dates of initiation of control during the crop period to achieve maximum yield are on the date of planting (0 DAP), 5 DAP, and 10 DAP for the 10-, 15- to 25-, and ≥30-m drain spacings when controlled at 30-cm height. The median preferable height of control when initiated at 20 DAP is 10 cm for ≤20-m drain spacing. No control is preferable when the drain spacing is >20 m. The height of control had more influence on simulated RY than the date of initiation of control for multiple drain spacings.
4. On average, with the best-case operation, DWM increased RY by approximately 0.8, 0.4, and 0.2% for the 10-, 20-, and 30-m drain spacings, respectively. The highest positive impact of DWM on RY (1.2% increase) was found in the cool, dry years and the greatest negative effect (0.2% reduction) was found in cool, wet years.
5. As drain spacing decreases, the preferred GDD for raising the outlet decreases and the API increases, indicating that these may be useful criteria for determining real-time operational strategies that reflect year-to-year climate variability. Further research is needed to determine to what degree this could be implemented based on real-time weather information, and the magnitude of potential benefits.
6. For narrower spacings, DWM can mitigate the increased NO_3 loss while positively impacting crop yields. These simulations suggest, however, that for spacings wider than 20 m it may be better to operate the DWM systems in the non-growing season only. Identifying appropriate drier and warmer years (based on API and GDD) in which crops may benefit from increased water availability and operating DWM systems in those years only could lead to a net increase in RY, however.

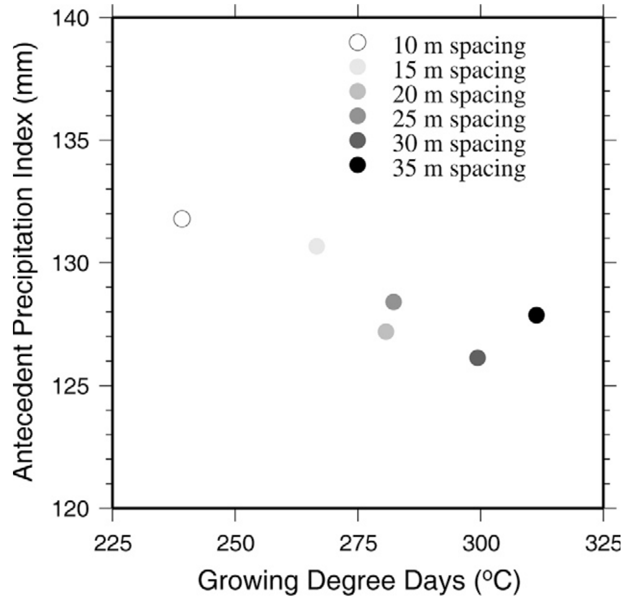

Fig. 10. Variation in mean growing degree days (GDD) and antecedent precipitation index (API) on the preferred dates of the initiation of outlet control to maximize yield, for all drain spacings when the outlet is raised to a height of 30 cm above the drain. Only the years between 1915 and 2006 for which the selected date impacted yield are included.

Acknowledgments

This material is based on work supported by the Cooperative State Research, Education, and Extension Service, USDA, under Agreement no. 2004-51130-02222, and the National Research Initiative, Water and Watersheds, USDA, under Agreement no. 08-35102-19259.

References

Ale, S., L.C. Bowling, S.M. Brouder, J.R. Frankenberger, and M.A. Youssef. 2009. Simulated effect of drainage water management operational strategy on hydrology and crop yield for Drummer soil in the midwestern United States. Agric. Water Manage. 96:653–665.

Betson, R.P., R.L. Tucker, and F.M. Haller. 1969. Using analytical methods to develop a surface runoff model. Water Resour. Res. 5:103–111.

Choudhury, B.J., and B.J. Blanchard. 1983. Simulating soil water recession coefficients for agricultural watersheds. Water Resour. Bull. 19:241–247.

Drury, C.F., C.S. Tan, J.D. Gaynor, T.O. Oloya, and T.W. Welacky. 1996. Influence of controlled drainage–subirrigation on surface and tile drainage nitrate loss. J. Environ. Qual. 25:317–324.

Economic Research Service. 1987. Farm drainage in the United States: History, status, and prospects. USDA-ERS Misc. Publ. 1455. U.S. Gov. Print. Office, Washington, DC.

Evans, R.O., R.W. Skaggs, and J.W. Gilliam. 1995. Controlled versus conventional drainage effects on water quality. J. Irrig. Drain. Eng. 121:271–276.

Fausey, N.R. 2004. Comparison of free drainage, controlled drainage, and subirrigation water management practices in an Ohio lakebed soil. Pap. 042237. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Fausey, N.R., K.W. King, B.J. Baker, and R.L. Cooper. 2004. Controlled drainage performance on Hotyville soil in Ohio. p. 84–88. *In* R. Cooke (ed.) Drainage VIII, Proc. Int. Symp., 8th, Sacramento, CA. 21–24 Mar. 2004. Publ. 701P0304. Am. Soc. Agric. Biol. Eng., St. Joseph, MI.

Frankenberger, J., E. Kladivko, G. Sands, D. Jaynes, N. Fausey, M. Helmers, R. Cooke, J. Strock, K. Nelson, and L. Brown. 2006. Questions and answers about drainage water management for the Midwest. Publ. WQ- 44. Available at www.ces.purdue.edu/extmedia/WQ/WQ-44.pdf (accessed Sept. 2007; verified 29 Oct. 2009). Purdue Univ. Coop. Ext. Serv., W. Lafayette, IN.

Hamlet, A.F., and D.P. Lettenmaier. 2005. Production of temporally consistent

gridded precipitation and temperature fields for the continental U.S. J. Hydrometeorol. 6:330–336.
Hofmann, B.S. 2002. Influence of tile spacing on crop yields, nitrate concentrations and nitrogen flux in drainage water. M.S. thesis. Purdue Univ., W. Lafayette, IN.
Hofmann, B.S., S.M. Brouder, and R.F. Turco. 2004. Tile spacing impacts on *Zea mays* L. yield and drainage water nitrate load. Ecol. Eng. 23:251–267.
Kalita, P.K., and R.S. Kanwar. 1993. Effect of water table management practices on the transport of nitrate-N to shallow groundwater. Trans. ASAE 36:413–422.
Kladivko, E.J., L.C. Brown, and J.L. Baker. 2001. Pesticide transport to subsurface tile drains in humid regions of North America. Crit. Rev. Environ. Sci. Technol. 31:1–62.
Kladivko, E.J., J.R. Frankenberger, D.B. Jaynes, D.W. Meek, B.J. Jenkinson, and N.R. Fausey. 2004. Nitrate leaching to subsurface drains as affected by drain spacing and changes in crop production system. J. Environ. Qual. 33:1803–1813.
Lalonde, V., C.A. Madramootoo, L. Trenholm, and R.S. Broughton. 1996. Effects of controlled drainage on nitrate concentrations in subsurface drain discharge. Agric. Water Manage. 29:187–199.
Luo, W., R.W. Skaggs, and G.M. Chescheir. 2000. DRAINMOD modifications for cold conditions. Trans. ASAE 43:1569–1582.
Luo, W., R.W. Skaggs, A. Madani, S. Cizikci, and A. Mavi. 2001. Predicting field hydrology in cold conditions with DRAINMOD. Trans. ASAE 44:825–834.
Ma, L., R.W. Malone, P. Heilman, D.B. Jaynes, L.R. Ahuja, S.A. Saseendran, R.S. Kanwar, and J.C. Ascough II. 2007. RZWQM simulated effects of crop rotation, tillage, and controlled drainage on crop yield and nitrate-N loss in drain flow. Geoderma 140:260–271.
Neild, R.E., and J.E. Newman. 1990. Growing season characteristics and requirements in the Corn Belt. Natl. Corn Handbk. 40. Available at www.ces.purdue.edu/extmedia/NCH/NCH-40.html (accessed 6 Nov. 2008; verified 29 Oct. 2009). Purdue Univ. Coop. Ext. Serv., W. Lafayette, IN.
Ruark, M.D., S.M. Brouder, and R.F. Turco. 2008. Dissolved organic carbon losses from tile drained agroecosystems. J. Environ. Qual. 38:1205–1215.
Singh, R., M.J. Helmers, W.G. Crumpton, and D.W. Lemke. 2007. Predicting effects of drainage water management in Iowa's subsurface drained landscapes. Agric. Water Manage. 92:162–170.
Sinha, T. 2008. Climate change impacts on the hydrologic role of seasonal soil frost in the northern midwestern United States. Ph.D. diss. Purdue Univ., W. Lafayette, IN.
Skaggs, R.W. 1978. A water management model for shallow water table soils. Tech. Rep. 134. Water Resour. Res. Inst., N. Carolina State Univ., Raleigh.
Skaggs, R.W. 1990. DRAINMOD user's manual. Biol. and Agric. Eng. Dep., N. Carolina State Univ., Raleigh.
Skaggs, R.W. 1991. Drainage. p. 205–243. *In* J. Hanks and J. Ritchie (ed.) Modeling plant and soil systems. Agron. Monogr. 31. ASA, CSSA, and SSSA, Madison, WI.
Soil Conservation Service. 1998. Soil survey of Tippecanoe County, Indiana. U.S. Gov. Print. Office, Washington, DC.
Soil Survey Staff. 2008. Official soil series descriptions. Available at soils.usda.gov/technical/classification/osd/index.html (accessed 7 Nov. 2008; verified 29 Oct. 2009). Natl. Soil Survey Ctr., Lincoln, NE.
Thorp, K.R., D.B. Jaynes, and R.W. Malone. 2008. Simulating the long-term performance of drainage water management across the midwestern United States. Trans. ASABE 51:961–976.
Wang, X., C.T. Mosley, J.R. Frankenberger, and E.J. Kladivko. 2006. Subsurface drain flow and crop yield predictions for different drain spacing using DRAINMOD. Agric. Water Manage. 79:113–136.
Wesström, I., and I. Messing. 2007. Effects of controlled drainage on N and P losses and N dynamics in a loamy sand with spring crops. Agric. Water Manage. 87:229–240.
Wesström, I., I. Messing, H. Linner, and J. Lindstrom. 2001. Controlled drainage: Effects on drain outflow and water quality. Agric. Water Manage. 47:85–100.
Wiskow, E., and R. van der Ploeg. 2003. Calculation of drain spacings for optimal rainstorm flood control. J. Hydrol. 272:163–174.