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Construction of critical periods for water resources management and their application in the FEW nexus

Val Z. Schull[1], Sushant Mehan[2], Margaret W. Gitau[1,*], David R. Johnson[3,4], Shweta Singh[1,5], Juan P. Sesmero[6], Dennis C. Flanagan[7,1]

[1] Department of Agricultural and Biological Engineering, Purdue University, West Lafayette, IN 47907, USA; vmijares@purdue.edu, mgitau@purdue.edu, singh294@purdue.edu, flanagan@purdue.edu
[2] Department of Food, Agricultural and Biological Engineering, Ohio State University, Columbus, OH 43210, USA; sushantmehan@gmail.com
[3] School of Industrial Engineering, Purdue University, West Lafayette, IN 47907, USA; davidjohnson@purdue.edu
[4] Department of Political Science, Purdue University, West Lafayette, IN 47907, USA
[5] Department of Environmental and Ecological Engineering, Purdue University, West Lafayette, IN 47907, USA
[6] Department of Agricultural Economics, Purdue University, West Lafayette, IN 47907, USA; jsesmero@purdue.edu
[7] USDA-Agricultural Research Service, National Soil Erosion Research Laboratory, West Lafayette, IN 47907, USA
* Correspondence: mgitau@purdue.edu

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Abstract Amidst growing population, urbanization, globalization, and economic growth, along with the impacts of climate change, decision-makers, stakeholders, and researchers need tools for better assessment and communication of the highly interconnected Food-Energy-Water (FEW) nexus. This study aimed to identify critical periods for water resources management for robust decision-making for water resources management at the nexus. Using a 4,610-ha agricultural watershed as a pilot site, historical data (2006–2012), scientific literature values, and SWAT model simulations were utilized to map out critical periods throughout the growing season of corn and soybeans. Results indicated that soil water deficits are primarily seen in June and July with average deficits and surpluses ranging from -134.7 mm to +145.3 mm during the study period. Corresponding water quality impacts include average monthly surface nitrate-N, subsurface nitrate-N, and soluble phosphorus losses of up to 0.026 kg/ha., 0.26 kg/ha, and 0.0013 kg/ha, respectively across the growing season. Estimated fuel requirements for the agricultural practices ranged from 24.7–170.3 L/ha, while estimated carbon emissions ranged from 0.3–2.7 kg CO_2/L. A composite look at all the FEW nexus elements showed that critical periods for water management in the study watershed occurred in the early and late season—primarily related to water quality—and mid-season, related to water quantity. This suggests the need to adapt agricultural and other management practices across the growing season in line with the respective water management needs. The FEW nexus assessment methodologies developed in this study provide a framework in which spatial, temporal, and literature data can be implemented for improved water resources management in other areas.

Keywords: food-energy-water nexus; water resources management; critical periods; decision-making; life cycle analysis; agricultural management

1. Introduction

With a changing climate, rapid population growth and urbanization, there is a growing concern about how to address the increasing and competing needs for food, energy, and water. The interdependence among food, energy, and water systems [1] and the competition between energy and food production for limited water resources [2], are the basis for the framework of the Food-Energy-Water (FEW) nexus. Water resources allocation and water quality are especially critical within the FEW nexus framework, as clean water is required for both food and energy production [2-4] yet both food and energy production have negative impacts on water quality [5]. Adverse impacts on water quality, in turn, have implications on the amount of water available for anthropogenic and ecosystem allocations. Thus, both aspects of water resources integrity (quantity and quality) need to be considered in FEW nexus assessments so as to avoid misconceptions related to the availability of water resources. In previous work [6] Schull et al. (2020) showed how a FEW nexus decision-making model—the WEF Nexus Tool 2.0 [3]—and results from the Soil and Water Assessment Tool (SWAT) [7], could be combined to give water-centric insights into interactions among FEW nexus sectors in an agricultural watershed through the end of the 21st century. In the study, average annual values were obtained and used to provide a broad picture of the interactions among FEW nexus components. Results, however, showed the need for finer-scaled evaluations as assessments on an average annual level could potentially mask the periods of time during which tradeoffs within the FEW nexus might be most critical for water management.

In particular, a detailed tracking of water availability and water quality on a monthly basis through the growing season would provide actionable insights on water-related aspects at the different crop-growth stages. Crop production requires not only water, but also energy. Farmers use a variety of tillage, planting, chemical application, and harvesting methods, and thus the amount of energy consumed is dependent on these practices. Evaluating energy usage and carbon emission across the growing season would provide a more accurate picture of how energy is consumed at the different crop growth stages, than would average annual values. For field operations, the most commonly used fuels are gasoline, diesel, and liquified petroleum gas [8]. With the use of fossil fuels as energy sources, it is necessary to calculate the carbon equivalent to gauge the environmental impact of agricultural production. Thus, even while addressing water resources management, it is important to quantify relationships and tradeoffs among the different sectors of the nexus [2] such that decision making is robust, and solutions are sustainable [9].

This study aims to identify critical periods for water resources management at the watershed scale and explore their potential for improving decision-making at the nexus. Specifically, to: (1) develop critical periods for water quantity and quality management in an agricultural system by identifying periods of water surplus and deficits based on historical data; (2) integrate energy, environmental, and cost impacts of agricultural production in water resources management; and, (3) make recommendations on the use of critical periods in developing sustainable and robust solutions at a watershed scale. This study uses the 4,610 ha (11,392 acres) Matson Ditch Watershed (Figure 1) in DeKalb County, northeastern Indiana, U.S., as a pilot site. The watershed was selected as it has sufficient data on land cover, crop yield, soil, management operations, and hydrological conditions to allow the different FEW nexus components in the watershed to be captured. Methodologies and approaches are applicable to other agricultural watersheds.

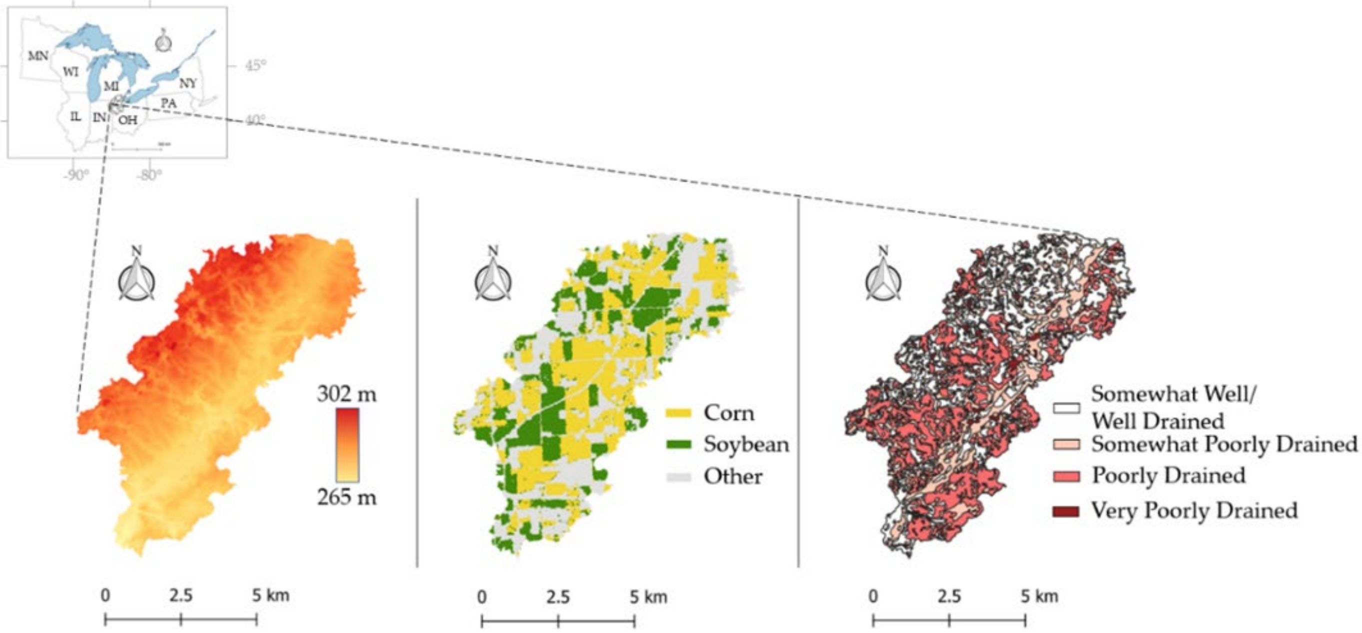


Figure 1. Topography, land cover (2011), and soil drainage classification of the Matson Ditch Watershed, Dekalb County, IN, USA.

1.2. FEW Nexus System for the Matson Ditch Watershed

The Matson Ditch Watershed FEW nexus system through the growing season is represented using Figure 2. The outer dashed line shows the system boundary and captures aspects of the FEW nexus that are being considered in the study. Due to the fluctuation in water, energy, and fertilizer demands, as well as prices and costs for each crop, the system schematic has been presented at the per hectare scale. The watershed is a rainfed predominantly sub-surface drained agricultural watershed [10]. Based on historical data from 2003–2012, annual precipitation averages around 1000 mm (39.4 in) [6,11-13]. Crop production in the watershed is reflective of the U.S. Midwest [14,15], with largely corn-soybean rotations covering 62.6% of the available agricultural land. Other land uses in the watershed include developed land (5%), pasture (13%), and, deciduous forest (9%), with smaller land uses occupying <10% of the land use area. This study focused only on corn and soybeans.

With respect to water quantity, losses in crop growth and yield could occur due to stresses from deficits in the amount of water available in the soil [16]. As with the larger Western Lake Erie Basin (WLEB) in which the study watershed is located, water quality concerns stem from pollutants from agricultural lands and include nutrients and pesticides [17,18]. The corn and soybean growing season in the study region runs from May through October, with most field operations occurring in early (tillage, planting, fertilizer and pesticide applications) and late season (harvesting). Agricultural tillage systems in DeKalb County are predominantly conventional tillage for corn and no-till for soybeans. According to the United States Energy Information Administration [19], in the state of Indiana the dominant energy sources are coal, natural gas, and gasoline. In terms of carbon emissions, Indiana is ranked as the 8th highest state based on 2017 data, and 11th highest in energy consumption per capita. The energy consumption and carbon emissions embedded in fertilizer and pesticide production are also included within the system boundary.

Details on how the different components are evaluated in this study are presented in the materials and methods sections. As assumptions, processes, and equations vary across the different sectors, each of the components is analyzed individually. Later, we discuss how the components interact with each other and combine results to provide an overall interpretation on critical periods for water management in the watershed.

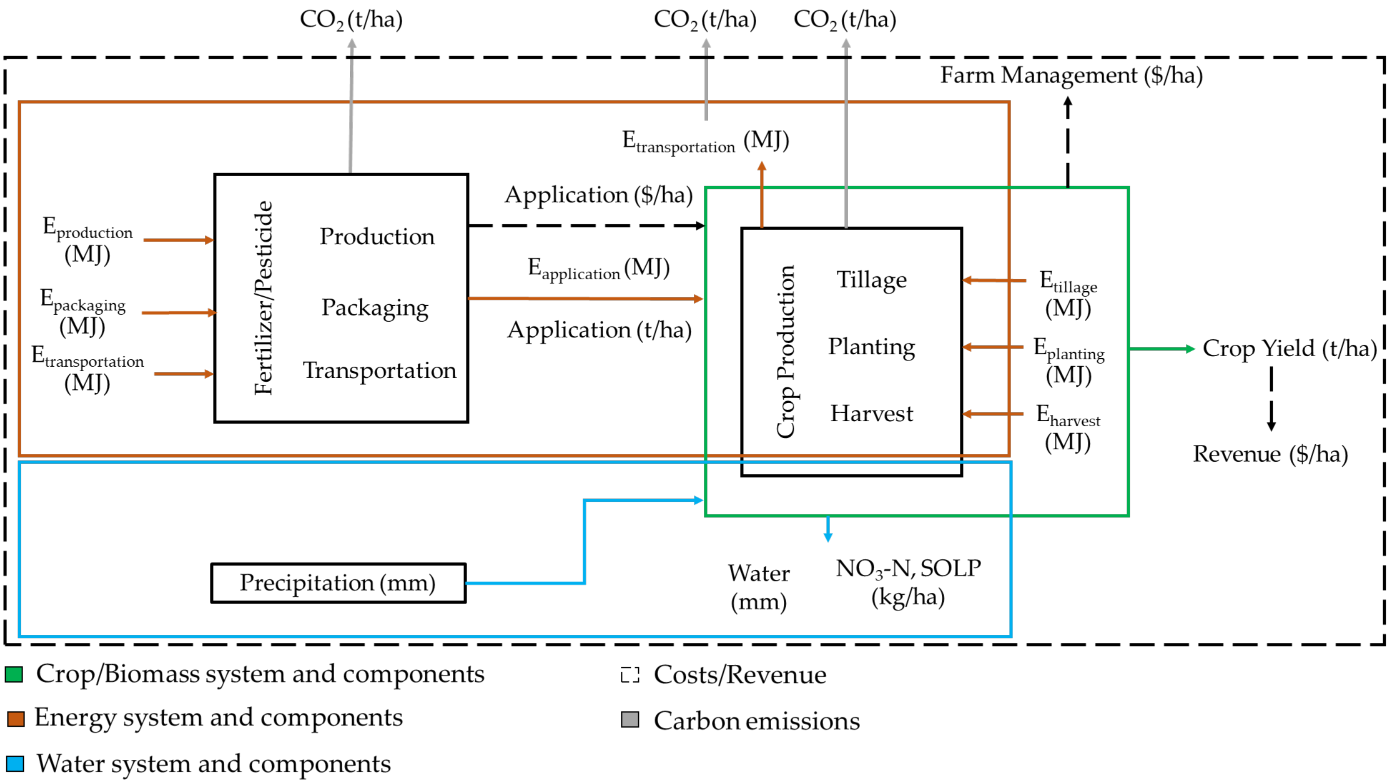


Figure 2. Schematic showing system and boundaries of the FEW nexus framework for the Matson Ditch Watershed downscaled on a hectare scale. Because the Matson Ditch Watershed is precipitation-fed, the water source comes only from precipitation (mm), with the nutrients of interest in this study being surface and subsurface nitrate (NO_3-N, kg/ha) and soluble phosphorus (SOLP, kg/ha). The energy use of each component is represented by $E_{component}$ (e.g. $E_{tillage}$) in MJ from fuel or electricity, with carbon emissions (CO_2, t/ha) being an output. Food production is represented by crop yield (t/ha) along with associated revenues ($/ha). Costs ($/ha) include fertilizer and pesticide application, and general costs of farm management.

2. Materials and Methods

2.1. Identifying Critical Periods for Water Quantity and Quality

In this study, critical periods for water quantity were determined through water balance evaluations and identification of periods of water surpluses and deficits based on results from SWAT. Critical periods for water quality were identified from periods in which the highest losses of phosphorus and nitrogen occurred, also based on SWAT model simulations. The analysis was conducted on a growing season basis (May through October), so as to better capture interactions among FEW nexus components. The study built on prior SWAT model assessments conducted in the watershed [12], in which the model had been set up to allow detailed evaluations of hydrology and nutrient yields in the watershed. Because the model had already been set up and had undergone a thorough calibration and validation in the previous work, this aspect of modeling was not repeated in this study. However, the model was re-run to provide the level of data needed for the planned analysis. To maintain consistency with the previous work, historical data from 2003–2012 were used to provide baseline runs for the watershed, with 2003–2005 being maintained as a warmup period.

2.1.1 Water Quantity

Figure 3 shows the hydrological system of the Matson Ditch Watershed. The input into the system is the precipitation, with the losses from the system being a summation of surface runoff, lateral flow, tile (subsurface drainage) flow, groundwater flow, and deep aquifer recharge. Effective precipitation is the amount of precipitation remaining after accounting for all losses; it is the precipitation that is stored in the root zone and is available for use by plants. The percentage of precipitation that is effective depends on factors such as climate, soil texture and structure, and the depth of the root zone [20]. The effective precipitation in any one month was calculated as (Equation 1):

$$\mathrm{P_{eff,m}} = \mathrm{P_m} - \left(\mathrm{SURQ_m} + \mathrm{WQ\ \ _m} + \mathrm{TILEQ_m} + \mathrm{LATQ_m} + \mathrm{DA_{rchg,m}}\right). \quad (1)$$

where, for any month m, $P_{eff,m}$ is the effective precipitation (mm), P_m is the precipitation (mm), $SURQ_m$ is the amount of surface runoff (mm), GWQ_m is the amount of groundwater flow (mm), $TILEQ_m$ is the amount of tile (subsurface drainage) flow (mm), $LATQ_m$ is the lateral flow (mm), and $DA_{rchg,m}$ is the deep aquifer recharge (mm).

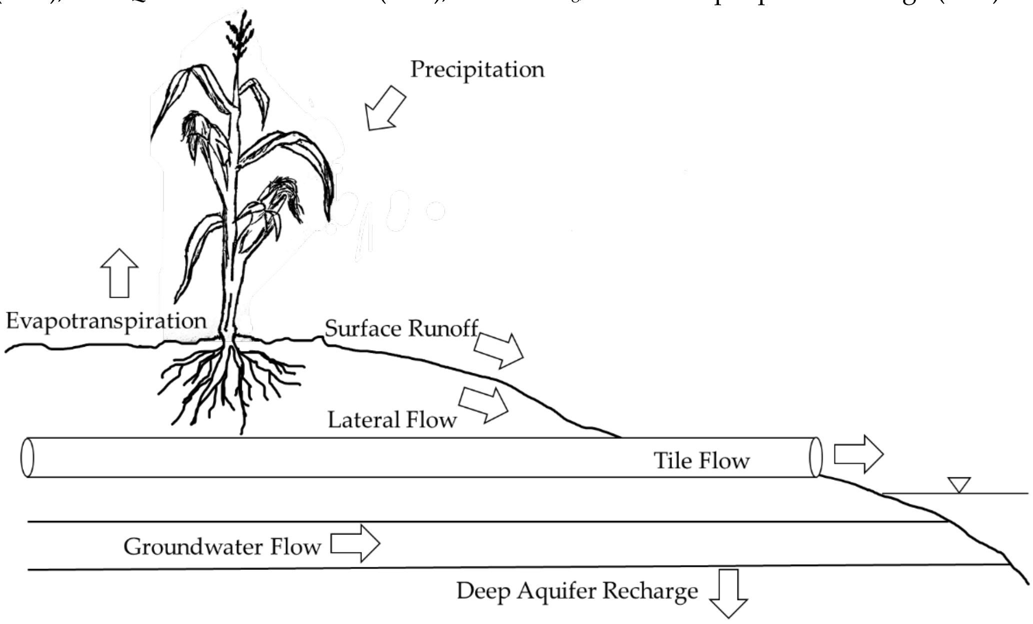


Figure 3. Hydrological system for the Matson Ditch Watershed.

The water surplus or deficit was determined as the difference between the effective precipitation and the amount of water required by the crops as determined based on the evapotranspiration (Equation 2):

$$\mathrm{D_{S,m}} = \mathrm{P_{eff,m}} - \mathrm{ET_m}. \quad (2)$$

where, for any month m, $D_{s,m}$ is the surplus or deficit (mm), $P_{eff,m}$ is the effective precipitation as calculated in Equation 1 (mm), and ET_m is the actual evapotranspiration (mm). If $D_{S,m}$ is positive, this means the effective precipitation is higher than the evapotranspiration and, thus, there is a surplus and water requirements for the crop are met effectively through precipitation; if $D_{S,m}$ is negative, the effective precipitation is less than the evapotranspiration thus there is a deficit and the crop would need to extract from available soil water reserve, if any, or depend on external inputs.

2.1.2 Water Quality

The water quality parameters that were evaluated in this study were soluble phosphorus (Sol P) and surface and subsurface nitrate (NO_3, TNO_3). As with water balance components, water quality parameter values were based on the model developed by Mehan et al. (2019a) [12]. Values were extracted and analyzed for all Hydrologic Response Units (HRUs) that had corn or soybeans land cover. In primarily sub-surface drained agricultural watersheds such as the Matson Ditch Watershed, water quality impacts of agricultural production are typically associated with the application of agricultural chemicals (fertilizers, pesticides) on agricultural fields [21,22], which typically coincides with the beginning of the growing season and the start of the spring rains. Thus, for this analysis, water quality parameters were aggregated and evaluated on a monthly basis for May through October of each year, and over the entire study period (2006–2012). The water quality parameters were then visualized across the growing seasons to determine the variation over the entire period.

2.2. Crop Growth

In SWAT, plant growth is modeled through simulating leaf area development, light interception, and conversion of intercepted light into biomass through the assumption of radiation-use efficiency based on the species of plant. Yield is calculated using an adjusted harvest index for a given day and the aboveground biomass [23]. For corn and soybeans, Equation 3 was used to calculate the yield,

$$\mathrm{yld} = \mathrm{bio_{ag}} \cdot \mathrm{HI}. \tag{3}$$

where yld is the crop yield (kg ha^{-1}), bio_{ag} is the aboveground live biomass on the day of the harvest (kg ha^{-1}), and HI is the adjusted harvest index on the harvest date (<1). Values obtained for yield during the period 2006–2012 were checked against historical data for the Matson Ditch Watershed. The historical data were obtained from the USDA National Agricultural Statistics Service (NASS).

2.3. Energy Usage and Carbon Emissions

As values for energy use and carbon emissions specific to the watershed were not available, regional values were used in this study. Generally, Cooperative Extension fact sheets, such as Downs and Hansen (1998) [8] and Hanna (2001) [24] provide farmers with guidance on inputs into their agricultural production, such as recommended fertilizer, pesticides, and fuel. In this study, fuel requirements for diesel were obtained from Hanna (2001) [24]. This author provided the fuel requirements for diesel; hence it was necessary to calculate equivalent values for the two other most common fuels used in agriculture, gasoline and liquified petroleum (LP) gas based on their respective energy content in comparison to diesel (Equation 4, [8]):

$$\mathrm{fuel_{est}}\left(\frac{\mathrm{L}}{\mathrm{ha}}\right) = 9.35394 \cdot \mathrm{diesel_{req}}\left(\frac{\mathrm{gal}}{\mathrm{ac}}\right) \cdot \mathrm{E_{ratio}} \cdot \tag{4}$$

where the fuel estimate ($fuel_{est}$) for the alternative fuel is calculated by multiplying the required amount of diesel ($diesel_{req}$) by the energy content ratio (E_{ratio}) between diesel and the alternative fuel. The value 9.35394 is a factor to convert values from imperial to metric units.

The type of fuel selected as an energy source will affect the amount of carbon being emitted during a specific agricultural practice. Estimates for carbon equivalents or carbon footprints associated with usage of fuel, fertilizers, and pesticides in agricultural systems were obtained based on greenhouse gas equivalencies calculations by government-level environmental protection agencies, such as the United States Environmental Protection Agency (USEPA) [25-27] and academic institutions [3,28-33]. Ranges of carbon emission equivalents for each of the farming practices, as well as the carbon equivalents per kilogram of energy source were obtained from Lal (2004) [28]. These carbon equivalent values were provided by kg of fuel. Using the values of average weight from Downs and Hansen (1998) [8], Equation 5 was used to convert values from Lal (2004) [28]:

$$CO_{2_{est}}\left(\frac{kg}{L}\right) = \frac{kg\ CO_2}{kg_{fuel}} \cdot \frac{lb}{gal_{fuel}} \cdot \frac{0.454\ kg}{1\ lb} \cdot \frac{1\ gal}{3.78541\ L}, \quad (5)$$

2.4. Cost Analysis in Decision-Making in the FEW nexus

In order to understand the impacts on cost of agricultural production, it was necessary to assess the economic costs of agricultural production. Both monthly and annual averages for price received for corn and soybeans in the state of Indiana were obtained from NASS. "Price received" for the crops is based on the data collected and the information received from the Agricultural Marketing Service. Monthly average state and national prices that producers received including market year averages are available from NASS. Monthly crop price received by farmers are available for the period 1970–2018. These values were implemented to provide indications on how the price received by farmers has changed over both the long-term and short-term. For this study, the Purdue Crop Cost and Return Guide archive was used to obtain estimates for earnings and losses for the period of 2006–2012. The Center for Commercial Agriculture has provided an archive since 2002 to project costs for the upcoming cropping year [34]. The costs that were taken into consideration included fertilizer, seed, pesticides, machinery (fuel, repairs, and ownership), hauling, interest, insurance, labor, as well as land. A range of potential values of earnings and losses across the state of Indiana were obtained by calculating earnings and losses per hectare for each crop, based on the assumptions of a 404.7 ha (1,000-acre) farm with corn and soybeans crop rotations. Overall market revenue per crop was calculated using Equation 6:

$$\text{Market Revenue}_{\text{crop}} = \text{Yield}_{\text{crop}} \cdot \text{Harvest Price}_{\text{crop}} \quad (6)$$

Government payments for the crops were based on the direct payment per crop, as shown in Equation 7:

$$\text{ov}\quad \text{Pay}_{\text{crop}} = \text{Direct Payment Yield}_{\text{crop}} \cdot \text{Direct Payment Price}_{\text{crop}} \quad (7)$$

The direct payment for corn was \$11.02/metric ton (\$0.28/bu) for corn and \$16.17/metric ton (\$0.44/bu) for soybean, with the direct payment based on direct payment yields for low, average, and high productivity soil.

Overhead costs—which include machinery ownership, family and hired labor, as well as land rent—for crop production were subtracted from the summation of the market revenue and government payment to obtain the overall earnings or losses, as indicated by Equation 8:

$$\text{EL}_{\text{crop}} = \left(\text{Market Revenue}_{\text{crop}} + \text{ov}\quad \text{Pay}_{\text{crop}}\right) - \text{Overhead}_{\text{crop}} \quad (8)$$

3. Results

3.1. Water Quantity

Figure 4 shows the range of values for monthly deficits and surpluses (a, b), along with average monthly precipitation, effective precipitation, and evapotranspiration (c, d) for the same crops. Data shown are averages for the period 2006–2012. In Figure 4 (a and b), the shaded region indicates the range of distribution of the D_S across all years. While both deficits and surpluses occurred throughout the growing season, for both corn and soybeans, deficits were more pronounced in mid-season, particularly in June and July (Figure 4). Deficits were also seen in August although this month also tended to have somewhat higher rainfall than the other two months, hence the deficits were generally less severe. These patterns were thought to be due to the green leaf area, as it plays an important role for evapotranspiration [35,36]. Stone (2003) [37] provides insight on which growth stages are most sensitive to water stress. For corn, water stress should be lessened in particular during the silking period, while for soybeans, it should be lessened during early to mid-bean fill [37]. Silking occurs about 69–76 days (mid-July) after seeding for a typical 120-day hybrid in the Corn Belt of the United States [38]. Early pod development for soybeans starts about 74–88 days (early to mid-August) from planting, with an additional 15–20 days to the middle of the seed filling [39]. Though these periods correlate with the highest number of days of stress per month according to the SWAT output, these sensitive growth stages correlate with a water deficit for corn at -23.50 mm (-0.93 in) and surplus for soybeans at 14.04 mm (0.55 in). Because the Matson Ditch Watershed is a precipitation-fed watershed with rapid aquifer recharge, a deficit does not necessarily mean that the crop is experiencing water stress, but that the crop needs from evapotranspiration exceed what is available through effective precipitation and, thus, that the crop would be drawing from storage.

Because P_{eff} is calculated based on the differences between the precipitation and the losses from the system, the amount of effective precipitation may vary with the hydrological conditions in the system. In the Matson Ditch

Watershed, the variation in P_{eff} is mainly driven by the surface and subsurface drainage for both corn and soybeans. Losses for corn were highest in May, with surface runoff being highest on average during this month (14.39 mm; 0.57 in). Average subsurface flow for corn ranged from 8.61–10.75 mm (0.34–0.42 in), with the highest flow occurring in August. For soybeans, May had surface runoff averaging 12.27 mm (0.48 in) and subsurface flow averaging 8.37mm (0.33 in). The largest combined losses occurred in June, with surface flow averaging 10.39 mm (0.41 in) and subsurface flow averaging 11.77 mm (0.46 in). Subsurface flow for soybeans peaked in August (13.21 mm; 0.52 in), with the end of the growing season having levels at 12.83 mm (0.51 in).

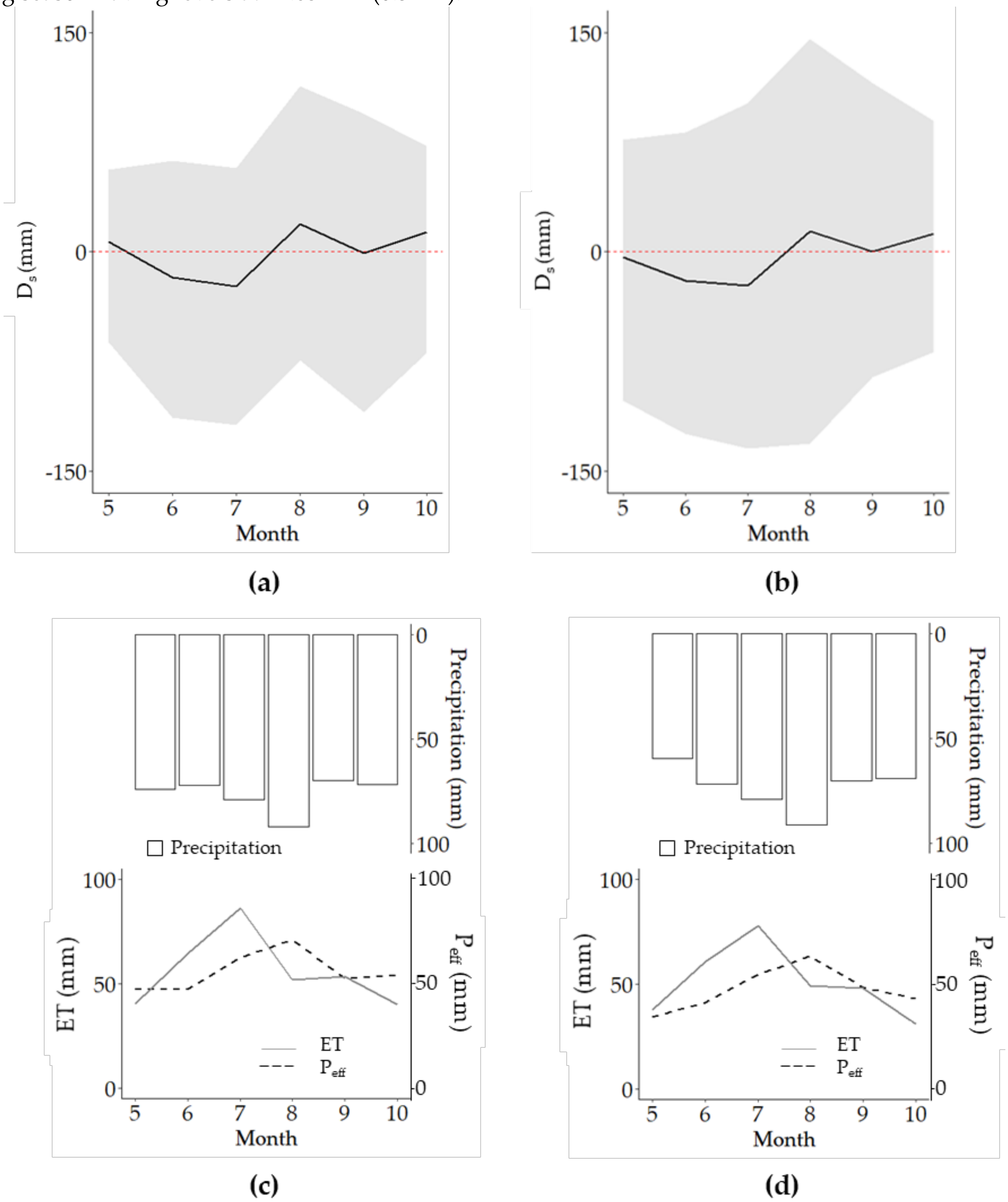


Figure 4. (a) Average monthly deficits (-ve) and surpluses (+ve) for corn; (b) Average monthly deficits (-ve) and surpluses (+ve) for soybeans; (c) Average monthly precipitation, effective precipitation (black dotted line), and evapotranspiration (grey solid line) for corn; (d) Average monthly precipitation, effective precipitation (black dotted line), and evapotranspiration (grey solid line) for soybeans. Shaded region indicates the range of distribution of the monthly D_s across all years.

Figure 5 shows the average evapotranspiration and effective precipitation, as well as deficits or surpluses through each growing season in 2006–2012 for both the corn and soybean crops. For corn, the smallest range of D_s was seen in

2012, with the range of the deficit and surplus being -91.27 mm – +54.94 mm (-3.59 in – +2.16 in). For soybeans, the smallest range of Ds occurred in 2006 with deficit values between -68.35 mm – 101.68 mm (-2.69 in – 4.00 in). The largest range of the deficit and surplus for corn was in 2007, with a range of -109.65 mm – +113.49 mm (-4.32 in – +4.47 in). For soybeans, this was also in 2007, with a range of -124.56 mm – +145.34 mm (-4.90 in – +5.72 in).

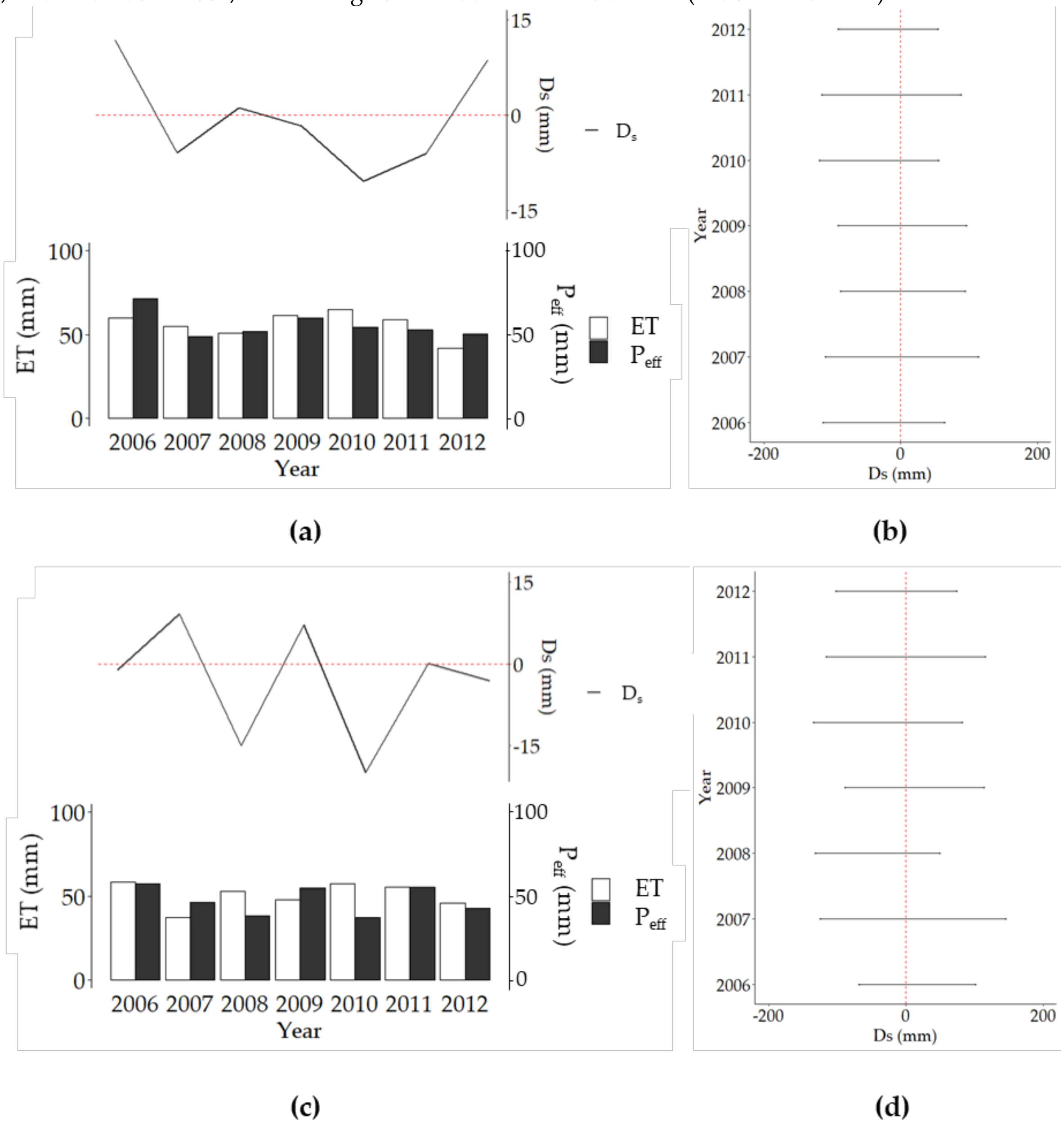


Figure 5. (**a**) Average effective precipitation (P_{eff}), evapotranspiration (ET), and deficit/surplus (D_s) for corn; (**b**) Annual range in deficit/surplus for corn; (**c**) Average effective precipitation (P_{eff}), evapotranspiration (ET), and deficit/surplus (D_s) for soybeans; (**d**) Annual range in deficit/surplus for soybeans.

Variations in temperature, frequency, antecedent soil moisture conditions, and intensity in rainfall can all affect the range for deficits and surpluses for crops. In 2006, the maximum temperature was 34.1°C (93.4°F) in July during the growing season, with a minimum of -3.33°C (26°F) in October. The maximum temperature for 2012 for the growing season was 38.5°C (101.3°F) in July, with a minimum in the growing season at -2.4°C (27.68°F) in October. Mehan (2018) indicated that the critical daily average temperatures for crop growth range from 20–25°C [11]. From 2006 to 2012, the number of days within this optimal temperature during the growing season ranged between 46 (2009) and 85 (2010). Higher daily temperatures could lead to heat stress and higher evapotranspiration rates [40]. Such climate shifts have already been documented [41-47] and could have effects on soil water reserves and other characteristics that affect water availability for cropland. It should be noted that the range of values for soybeans is much more pronounced than that of corn. This could be because soybeans are not as severely affected by drought as corn [48], and thus may be more adaptable to changes in climate. This inference aligns with findings from Mehan et al. (2019a) [12] indicating that future yields for soybeans in the Matson Ditch Watershed were projected to be higher than baseline values. Hatfield et al. (2018) [43] showed that corn yields would significantly decrease in the Midwest due to increases in temperature, while soybeans would be more affected by water availability.

3.2. Water Quality

Figure 6 shows the monthly averages for nitrate-N losses in surface runoff (NSURQ), tile (subsurface drainage) nitrate-N losses (TNO_3), and soluble phosphorus losses (Sol P) losses from each crop type. The shaded region indicates the range of monthly average distributions across all the growing periods for 2006–2012. For surface nitrate-N losses, the average values in May were 1.48 $\times 10^{-1}$ kg/ha and 1.22 $\times 10^{-3}$ kg/ha for corn and soybeans, respectively. For corn, there was a decline for June (4.47 $\times 10^{-3}$) and July (1.49 $\times 10^{-6}$), but a slight increase in August (9.39 $\times 10^{-5}$ kg/ha) and September (8.47 $\times 10^{-5}$) with the October average of surface nitrate at 1.66 $\times 10^{-4}$ kg/ha. For soybeans, the values of surface nitrate decreased after May, with the lowest value in June at 2.49 $\times 10^{-5}$ kg/ha and increasing in July (4.97 $\times 10^{-5}$ kg/ha) and August (7.65 $\times 10^{-5}$ kg/ha). There was a slight dip in the average in September (5.77 $\times 10^{-5}$ kg/ha) and then an increase in the harvesting month of October (2.58 $\times 10^{-2}$ kg/ha). The average value of subsurface nitrate-N losses during May was 1.89 $\times 10^{-1}$ kg/ha for corn and 1.09 $\times 10^{-1}$ kg/ha for soybeans. For corn, the average declined in June (2.72 $\times 10^{-2}$ kg/ha), with the lowest value being simulated in July (2.68 $\times 10^{-3}$ kg/ha). Increases were seen in August (2.55 $\times 10^{-2}$ kg/ha) and September (8.40 $\times 10^{-2}$ kg/ha), with the value at the end of the growing season (October) being 1.27 $\times 10^{-1}$ kg/ha. For soybeans, there was an increase in the monthly average of June to 2.58 $\times 10^{-1}$ kg/ha. In July, the monthly average declined to 1.25 $\times 10^{-1}$ kg/ha and decreased in August (4.14 $\times 10^{-2}$ kg/ha) and September (3.78 $\times 10^{-2}$ kg/ha). A slight increase was observed for October (7.25 $\times 10^{-2}$ kg/ha). For soluble phosphorus losses, there was a decline in monthly averages through the growing periods of soybeans, with a slight increase in monthly averages for corn. For corn, the average soluble phosphorus loss at the start of the growing season was 5.67$\times 10^{-4}$ kg/ha and the season ended with an average value of 8.40 $\times 10^{-4}$ kg/ha. For soybeans, the monthly values of soluble phosphorus losses began at 7.73 $\times 10^{-4}$ kg/ha and ended at 5.95 $\times 10^{-4}$ kg/ha. The increases during the late summer months of July (corn: 1.56 $\times 10^{-4}$ kg/ha; soybean: 8.94 $\times 10^{-4}$ kg/ha) and August (corn peak at 1.29 $\times 10^{-3}$ kg/ha; soybean peak at 9.40 $\times 10^{-4}$ kg/ha) were due to subsurface flow. For both soluble phosphorus and nitrate-N, higher loadings were simulated during the months in which agronomic practices occurred, making these critical periods for water quality. Results, however, suggested the need to monitor contaminant transport during the growing season particularly as related to subsurface losses. Capturing these critical periods allows decision-makers to understand the relationships in water quantity and quality issues on a watershed-scale basis.

3.3. Crop Growth

Yield values from the SWAT output, as well as the observed values from NASS are shown in Table 1. The observed NASS crop yield averages for 2006–2012 were 8.1 ± 1.3 t/ha for corn and 2.8 ± 0.3 t/ha for corn and soybean, respectively, compared to 6.5 ± 1.3 t/ha and 2.6 ± 1.4 t/ha for the simulated value. Overall, the comparison between the observed and simulated yields indicated that the SWAT model adequately captured crop growth in the Matson Ditch Watershed. It also provided confirmation that though deficits were experienced within the watershed, the crops did not experience stress and had enough water to sustain their growth. This is reasonable, as the Matson Ditch Watershed is a precipitation-fed system with adequate yields being obtained without the need for irrigation. The output of crop yields is important in relation to critical periods as it provides context on why there are stressors within the nexus. By temporally mapping the harvest of these crops in October, it provides a tradeoff that occurs in the nexus; the yield of the crops comes at the cost of water quality, in which several water quality parameters are seen to increase in the month of October.

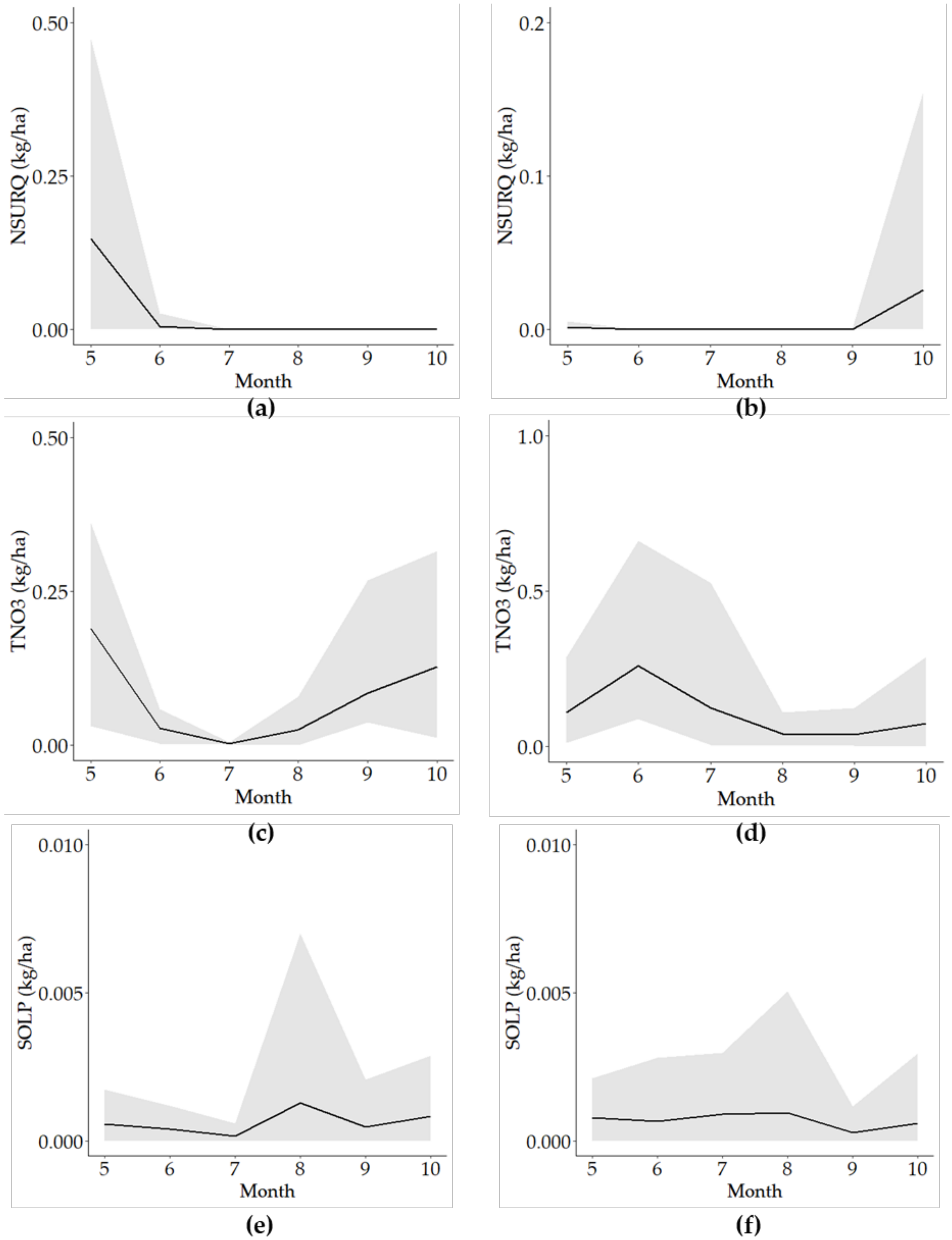


Figure 6. Monthly average nutrient losses from crops in the Matson Ditch Watershed for 2006–2012: (**a**) surface NO_3-N for corn; (**b**) surface NO_3-N for soybeans; (**c**) subsurface drainage NO_3-N for corn; (**d**) subsurface drainage NO_3-N for soybeans; (e) soluble P for corn; (f) soluble P for soybeans. Shaded regions indicate the range of distribution of the monthly nutrient load across all years.

Table 1. USDA NASS DeKalb County crop yields for 2006–2012.

Year	Yield (t/ha)			
	Corn		Soybeans	
	Observed	Simulated	Observed	Simulated
2006	9.2	6.5	3.0	1.5
2007	9.2	4.5	3.0	3.8
2008	7.6	6.5	2.1	0.5
2009	9.4	8.1	3.0	1.5
2010	7.7	8.2	2.6	4.2
2011	7.8	5.8	2.7	3.7
2012	5.7	5.6	3.0	2.7

3.4. Energy Consumption and Carbon Emissions

The agronomic practices and management operations for corn and soybeans are shown in Table 2. This outlines the timeline for which nutrient and pesticide application occurs, as well as the type of tillage that is used with each crop type within the watershed. The timing of these practices captures critical periods for both energy usages and carbon emissions as these are associated with tillage, planting, fertilizer and pesticide applications, and harvesting. No energy is required for water application as the watershed is precipitation-fed. Furthermore, this timing is associated with the water balance through the growing stages of the crop—discussed earlier in the text—and affects the amount and availability of nutrients for transport within the system. Table 3 shows the gallons of fuel required per crop hectare based on the agronomic activities for the Matson Ditch Watershed and the calculated values for carbon emission per liter based on the fuel type found in various sources. The carbon footprint per hectare was calculated by summing the most appropriate fuel requirement based on the field operation as documented in Downs and Hansen (1998) [8], Hanna (2001) [24], and Lal (2004) [28], including fertilization application, tillage, planting, harvesting, and hauling. It was assumed that the crop would be hauled up to half a mile (0.805 km) off the field. The range in carbon emission coefficients shows there is uncertainty in calculating the carbon equivalent for various energy sources, and thus for the Matson Ditch Watershed, decision-makers can estimate the total amount of fuel and carbon emissions based on site-specific agronomic practices.

Table 2. Agronomic practices or management operations for different land use/ land cover for the Matson Ditch Watershed [11,49].

Crop	Date	Management Operation	Rate
Corn	22 – April	Nitrogen Application (as Anhydrous Ammonia)	176.0 kg/ha
	22 – April	(P_2O_5) Application (DAP/MAP)	54.0 kg/ha
	22 – April	Pesticide Application	2.2 kg/ha
	6 – May	Tillage – Offset Disk (60% mixing)	
	6 – May	Planting – Row Planter, double disk openers	
	10 – October	Harvest	
Soybeans	10 – May	(P_2O_5) Application (DAP/MAP)	40.0 kg/ha
	24 – May	No – tillage planting – Drills	
	7 – October	Harvest	
	20 – October	Tillage, Chisel (30% mixing)	

Table 3. Estimated range of fuel required (L/ha) for agronomic practices and management operations based on crop and fuel type.

Crop	Fuel Type	Fuel Required (L/ha) Downs and Hansen (1998); Hanna (2001) [8, 23]	Lal (2004) [28]†
Corn	Diesel	(36.7, 58.9)	(36.9, 69.3)
	Gasoline	(40.8*, 42.1)	(46.1, 85.5)
	LP Gas	(54.9*, 70.8)	(90.8, 170.3)
Soybeans	Diesel	(26.2, 49.1)	(24.7, 42.8)
	Gasoline	(29.1*, 35.0)	(30.9, 53.4)
	LP Gas	(39.2*, 59.0)	(61.6, 102.0)

Fuel Type	Carbon Emissions ($kg\ CO_2/L$) Daher (2012) [3]	Lal (2004) [28]	USEPA (2008) [25]	USEPA (2014) [26]	USEIA (2019) [50]	USEPA (2020) [27]
Diesel	2.6	0.8**		2.7	2.7	2.7
Gasoline	2.4	0.6**		2.3	2.3	2.3
LP Gas	2.3	0.3**	1.7	1.5		

*Calculated from diesel requirements and Equation 3. **Calculated using Equation 4.
†Converted from kg CE values based on fuel weight

Table 4 outlines the estimated energy required and the carbon equivalent per kg of active ingredient (ai) estimated for the Matson Ditch Watershed based on literature for carbon footprint and equivalent of these chemicals. As inputs for energy are outlined based on the agronomic practices occurring throughout the year, these values are applicable to the growing season in general. For irrigated systems, it would be important to also calculate monthly energy use requirements of pumping and transporting the water to fields through the growing season. Furthermore, carbon emissions from different energy sources could be assessed to provide watershed managers and decision-makers an understanding on the tradeoffs in renewable and nonrenewable energy sources.

Table 4. Estimates of total energy (MJ/kg ai) and carbon equivalent ($kg\ CO_2/kg$ ai) for fertilizer and pesticide production, packaging, and transport for the Matson Ditch Watershed.

Estimates	Chemical: Anhydrous Ammonia	P_2O_5 (DAP/MAP)	Atrazine	References
Total MJ/kg ai	63	18	208	[29,51,52]
	67	17.4	189	[29,51,52]
			190	[29,53]
Total $kg\ CO_2/kg$ ai	(0.9–1.8)	(0.1–0.3)	3.8	[28]
	4.8	0.73	23.1	[30]
	2.52	0.73		[31]
	1.3	0.2	6.3	[32]
	1.74	0.33		[33]

*ai = active ingredient

3.5. Cost Assessment of the FEW Nexus

Based on the analysis of all available NASS data (1970–2018) there was an increase in price received for corn and soybeans over time ($\tau = 0.3749$, $p < 0.0001$ for corn, $\tau = 0.5732$, $p < 0.0001$ for soybeans). However, this does not necessarily consider potential increases in costs for agronomic inputs, such as machinery maintenance, chemical application, labor, rent, etc. Hence these inputs were taken into account through short-term assessment. The earnings and losses shown in Table 5 were based on a 1,000-acre (404.7 ha) farm in Indiana with corn and soybeans rotations, as previously discussed. These values reflect the profitability, which is the difference between the price received multiplied by the yield and the government subsidies (thus, revenue) and the cost of the crop. While the revenue from a crop is not realized until after the growing season, the cost inputs of agronomic practices tend to occur at the beginning of the growing season, thus, these values reflect the costs over the growing period.

The earnings and losses can be explained from historical context. In 2003, a summer drought in the Midwest caused yields for corn and soybeans to be reduced [54], which meant crops were severely stressed. Though still operating at losses in 2004, losses were not as great as those in 2003. According to the Committee on Water Implication of Biofuels Production in the United States in the National Academies of Sciences, Engineering, and Medicine [55], after Hurricane Katrina in 2005, there was a surge in the price of oil, causing an interest in ethanol production due to the low corn prices. The federal government encouraged corn and soybean production with an ethanol subsidy through the Energy Act of 2005 [55]. In 2006, the governor of Indiana announced plans for the state to shift to cellulosic and biomass fuel production. With Indiana being one of the top soy and corn producers in the country, this made the state a suitable candidate for biodiesel production [56]. This, in combination with policies implemented by several countries that constrained corn and soybean supply in the world market, likely added upward pressure to the price of corn and soybean prices [57], which is reflected in the results found. After 2008, there was a decline in demand for agricultural commodities due to the recession, so the profitability of corn and soybeans was reduced [54,55]. These values correspond with insights from Langemeier (2017), that indicated that from 2007–2013, corn production was relatively more profitable than soybeans on an average farm in Indiana [58].

Table 5. Ranges of estimated earnings (+ve) or losses (-ve) per ha for 2003–2012 for a medium-sized farm in Indiana.

	Earnings/Losses per ha	
Year	**Corn**	**Soybeans**
2003	(-$126.67, -$65.04)	(-$212.00, -$152.69)
2004	(-$116.83, -$97.38)	(-$123.70, $12.17)
2005	(-$196.55, -$166.66)	(-$236.77, -$171.57)
2006	(-$199.37, -$184.03)	(-$207.62, -$125.37)
2007	($216.90, $559.50)	($17.02, $240.80)
2008	($151.87, $687.56)	($211.39, $609.74)
2009	(-$297.86, $45.09)	(-$290.97, -$115.02)
2010	(-$52.24, $317.40)	(-$142.46, $87.85)
2011	($259.76, $838.84)	($149.81, $571.39)
2012	($72.80, $614.92)	(-$20.64, $310.49)

3.6. Interactions Among FEW Nexus Components in the Matson Ditch Watershed

Figure 7 shows how critical periods for the different FEW nexus components can be mapped out across the growing period for decision-making. Inputs and outputs associated with the food and energy components typically occur at the beginning and the end of the growing season as they are associated with farming operations including tillage, planting, and fertilizer applications—which occur at the beginning of the growing season—and harvesting and yields—which occur at the end of the growing season. However, operations occurring mid-season could also have impacts. For example, a post-emergence herbicide application occurring around June is a typical agronomic practice for soybeans in Indiana [59]. While not included in this study, such operations would have associated energy consumption and carbon emissions that would occur during the growing season. Depending on the operation, there could be water quality implications associated with the application or with any soil disturbances that occur. In contrast, both water quantity and quality components varied across the growing season and for the different crops. Nonetheless, there were distinct periods in which water deficits occurred, generally during the period when the crop is actively growing. In the study watershed, the crops were generally able to draw from soil storage when deficits occurred. In areas where substantial deficits occur, irrigation would be necessary to avoid yield losses. Introducing irrigation to a system has implications on energy use and carbon emissions [60]. Furthermore, irrigation has implications for pollutant transport and, thus, could introduce critical periods for water quality in mid-season. Even in areas such as the study watershed, supplemental irrigation has been shown to increase crop yields. Thus, opportunities for potentially water quality-friendly practices—such as drainage water recycling [61] — could be explored. With respect to water quality, key management interventions would be needed at the beginning and towards the end of the growing season. Some of these could entail changes in farming operations, for example, the timing or method of fertilizer applications to minimize pollutant availability for transport thorough surface and/or subsurface pathways. This could have implications on energy use and carbon emissions. Regardless, farmers would be concerned about the implications of changing management practices on yields and overall costs of crop production. Thus, concerted efforts would be needed to optimize management practices so as to minimize water quality impacts while ensuring farming remains profitable [62].

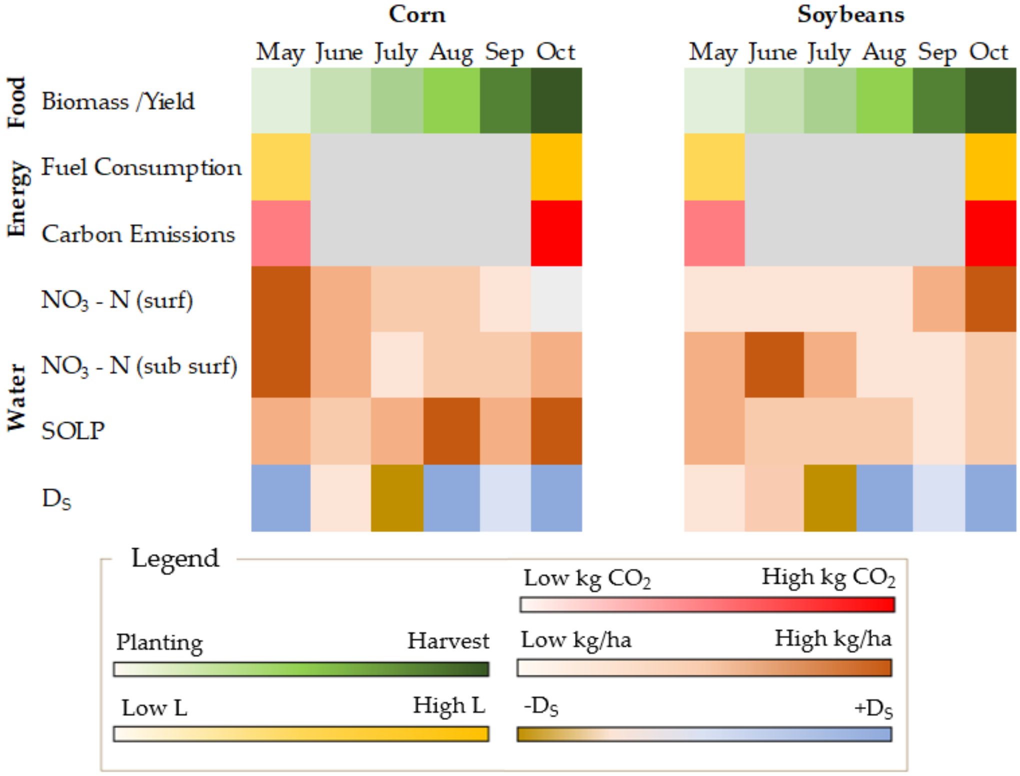


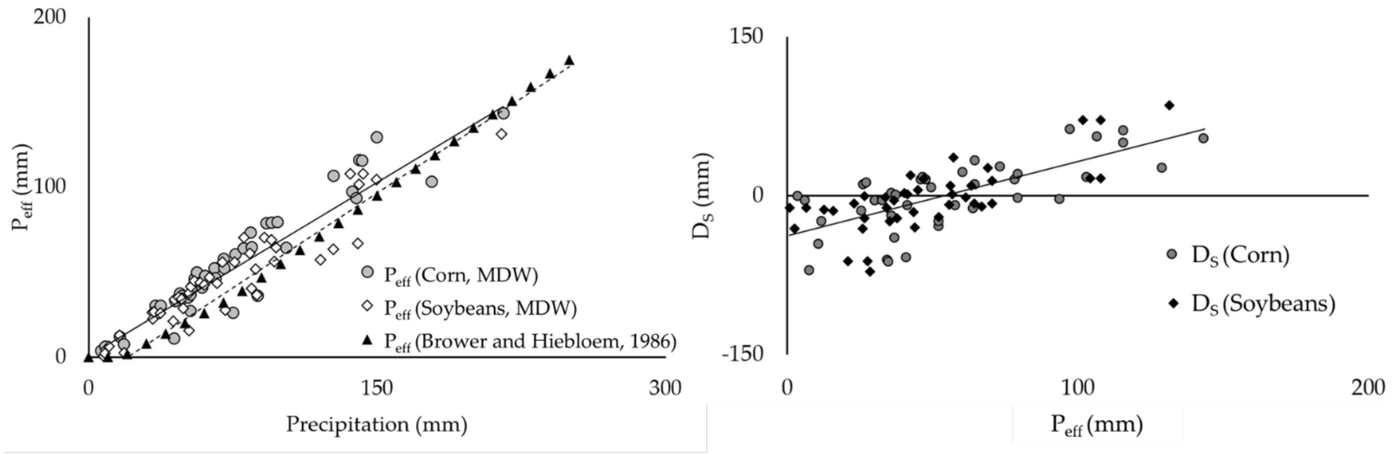
Figure 7. Summary of monthly (May–October) patterns for corn and soybeans in the Matson Ditch Watershed across the various aspects of the FEW nexus during the 2006–2012 time period. The color-scales indicate low values with lighter colors and higher values with darker colors. For food: the crops continue to grow until at the end of the growing season, in this case, in October. For energy: fuel usage and carbon emissions for each year can be determined for the agronomic calendars for each crop, along with their associated carbon emissions. For water: water quality loads for various pollutants (surface nitrate, NO_3-N (surf); subsurface nitrate, NO_3-N (sub surf); and soluble phosphorus, SOLP) are mapped out across the growing season for each crop. For water quantity, deficits and surpluses (D_S) are indicated for each month for each crop.

4. Discussion

Given the intricate links among food, energy, and water, the competition for water between the food and energy sectors, and the negative effects these two sectors often have on water, assessments considering all three sectors in concert are key to developing long-term solutions for water management. While most associated analyses are conducted on an annual or average annual basis, this study considered monthly timeframes across the crop growing season. This level of analysis provided insights into critical periods for water resources management considering both quantity and quality, and allowed other aspects of the nexus to be integrated at the same level.

When addressing the water demands of corn and soybeans, it is necessary to understand that there are various factors that can play a role. According to the FAO, corn requires about 500–800 mm per growing period, with soybeans requiring 450–700 mm [20]. The actual amount of precipitation available to the crop can be determined by calculating the effective rainfall, which can be obtained by subtracting losses other than evapotranspiration from the total precipitation. Site-specific water balances can be obtained using a hydrological modeling approach, which also helps better attribute periods of water stress. However, depending on the model, a substantial amount of data might be required. In the absence of detailed data, the FAO provides a chart that could be used to calculate effective precipitation [20]. However various factors can affect effective precipitation, including soil moisture status, crop characteristics, climatic conditions, and hydrological conditions due to geographic location [63], and thus the chart might not always provide a representative picture. Correlations between precipitation and effective precipitation (P_{eff}), and those between effective precipitation and deficits or surpluses (D_S) could be constructed for different crops in areas or periods with data (Figure

8) and used in subsequent assessments or other assessments in the same or similar region. For the Matson Ditch Watershed, for example, the chart obtained for P_{eff} compared well to that provided by the FAO (Figure 8a), and inferences could potentially be made on D_S based on P_{eff} (Figure 8b). Corresponding correlations (Spearman's ϱ) between precipitation and $P_{eff,}$ and P_{eff} and D_S were 0.9239 and 0.6891, respectively, while that betwee precipitation and D_S was 0.6344. All correlation values were significant ($p<0.0001$). Thus, in cases where it would be difficult to quantify losses due to data limitations, P_{eff} and/or D_S could still be estimated as long as precipitation data are available.



(a) **(b)**

Figure 7. Scatter plots for the Matson Ditch Watershed (MDW) showing: (a) effective precipitation (P_{eff}) for corn and soybeans vs. monthly average precipitation compared to the effective precipitation (P_{eff}) vs. precipitation curve provided by the FAO [24]; and, (b) deficits or surpluses (D_S) vs. monthly average effective precipitation.

Though the Matson Ditch is a precipitation-fed watershed, the amount of soil water reserve that is available to plants can become significantly reduced, based on study results. Losses in crop growth and yield may occur due to stress from a deficit in the availability in the amount of water in the soil [16]. In our study, though there were months in which deficits were observed, the crops were able to rely on soil moisture storage and were not adversely affected. This might not be the case in other watersheds. Methodologies used in this study can be applied in other areas to identify critical periods and help identify where additional efforts are needed to better manage water availability. With respect to water quality, the situation in the Matson Ditch Watershed is reflective of the agricultural industry. Nonpoint source pollution from agriculture impairs 48% of rivers in the United States [64], with primary concerns being phosphorus and nitrogen. In high concentrations, soluble phosphorus and nitrogen can become detrimental to water quality [65-68]. Phosphorus creates eutrophic water conditions that deplete oxygen and heighten hypoxic conditions [69-72]. Soluble reactive phosphorus, due to its bioavailability, is often the limiting nutrient in fresh waters, thus it is critical to prevent this type of phosphorus from entering susceptible bodies of water [73]. Nitrogen in excessive levels may deplete dissolved oxygen supply and contribute to cyanobacteria growth [73]. Nitrogen paired with phosphorus can affect the prevalence of and toxicity of HABs [74-76]. Because of degradation of land and water resources, individual farmers and communities may have to make critical investments to reverse the situation [77]. Government programs that aid in minimizing the cost of sustainable farming practices are available in the United States. In the larger Western Lake Erie Basin, farmers are implementing Best Management Practices (BMPs) on a voluntary basis [78]. With programs such as the 4R Nutrient Stewardship Program, government agencies and farmers work together to optimize farming practices [79] to minimize environmental impacts while continuing to support the viability of farming.

Carbon footprints and carbon emission assessments for farming operations and energy sources required in the agricultural system of interest provide another context that may be of interest to decision-makers. Most FEW nexus assessments focus on greenhouse gas and carbon emissions in relation to energy consumption [80]. To quantify the relationship pathways outlined, values from literature representative of the Matson Ditch Watershed were implemented for energy efficiency and carbon emission concerns that may be of interest to decision-makers or stakeholders. These included fertilizer and pesticides as they are significant secondary sources of carbon emissions in agriculture [28]. Including aspects of agricultural production that occur outside of the growing period would provide an expanded view of the life cycle of agricultural chemical usage through their energy and carbon emissions. Because the focus of this study was in the development of critical periods for water resources management in agricultural systems, analysis was kept to the growing period.

With respect to the cost analysis, it was necessary to not just look at the price received by the farmer, but also to address profits or losses. Using the Purdue Crop Cost and Return Guide allowed us to develop an understanding of realistic scenarios for earnings and losses in crop production. Though the assumption for this study was that everything grown was sold at the end of the season, there is potential for storage of grains for later sale [81]. Additionally, cost assessment is much more complex, as the economic value of crops shifts. As noted previously, policy initiatives can influence the profitability of certain crop production and alter the tradeoffs when selecting which crops to produce. This highlights that though policy could allow for differences in behavior, it can also allow for current practices to continue. It also brings forth the point that policy effects are difficult to predict. When evaluating the cost aspects of the FEW nexus, it is, thus, necessary to understand that policy and other cost factors can play a role in profitability of agricultural production.

5. Conclusions

Because of the major role that water quality and quantity play in the FEW nexus, constructing critical periods for water management is important. This study outlined critical periods for various FEW nexus components during the growing season. The amount of water required by crops varied through the season, with needs for corn and soybeans being greatest during the summer months. Water quality was influenced by agronomic practices, with subsurface nitrate-N losses simulated throughout the growing season due to subsurface flow. In general, critical periods for water quality in the study watershed occurred in the early and late season while those for water quantity occurred in mid-season. Any changes to current practice could potentially shift this pattern, particularly as related to water quality. Results suggested the need to adapt agricultural and other management practices across the growing season in line with the respective water resource management needs. It was, however, recognized that such adaptations could have implications for crop yields, energy usage, and carbon emissions which could, in turn, affect farming profitability. This pointed to the need for an optimization approach to finding water management solutions at the nexus. The methodology developed in this study provides a framework through which spatial, temporal, and literature data can be used to conduct FEW nexus-based assessments on a monthly scale with a view to capturing FEW nexus elements as related to critical periods for water management. This provides an additional level of information for decision-makers and stakeholders, apart from the annual or average annual picture, which helps better address water resources concerns. Results showed that through the integration of representative values for energy consumption and carbon emissions for field operations and profitability, a more holistic view of component interactions at the FEW nexus could be developed to improve decision-making. Finally, this methodology could be implemented in other areas with similar needs.

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