Net Daily Metabolism in Agricultural Drainage Ditches

by

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ABSTRACT

Headwater streams in areas of intensive agriculture are frequently modified through surface and subsurface drainage to increase the transport of water to downstream water bodies and improve cropland in poorly drained areas. Stream modification and subsequent maintenance practices are beneficial to farmers but likely impair stream ecosystem function. Fluvial processes in these overly-widened headwater streams naturally form sediment benches that are stabilized through the establishment of grasses. Because these grassed benches have the potential to take up nutrients and decrease sediment export, they may improve the ecological functioning of modified headwater streams. To evaluate this, I determined whole stream metabolism for three types of headwater streams; reference streams, traditional trapezoidal-shaped drainage ditches, and drainage ditches that had developed grassed benches. I tested whether trapezoidal-shaped drainage ditches and benched drainage ditches functioned similarly to natural (reference) headwater streams in terms of net daily metabolism (oxygen production and consumption), and examined environmental and water quality variables that could influence the rates of net daily metabolism in each type of headwater stream. I found that rates of net daily metabolism were most similar in trapezoidal ditches and reference streams, but that trapezoidal ditches and benched ditches were more directly comparable in terms of overall ecosystem function due to the impacts of agricultural activities on these two systems. My study suggests that the benched system had a greater capacity for nutrient uptake and suspended sediment reduction and therefore provided more opportunities for improved water quality and ecological functioning in agricultural drainage ditches.

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TABLE OF CONTENTS

Page

LIST OF TABLES AND FIGURES

INTRODUCTION

In highly agricultural areas of the Midwest, headwater streams are frequently modified through surface or subsurface drainage in order to increase the transport of water to downstream water bodies and improve cropland in poorly drained areas (Fausey *et al.* 1995, Landwehr and Rhoads 2003). Existing stream channels are often widened, deepened, and straightened resulting in channels that lack physical, morphological, and riparian heterogeneity and are trapezoidal in shape (Rhoads and Herricks 1996). Maintenance of modified channels occurs regularly and consists of clearing the channel of vegetation and sediment that has accumulated over time (Landwehr and Rhoads 2003, Urban and Rhoads 2003, Jayakaran *et al.* 2005). In addition, field tiles to enhance sub-surface drainage and lower the water table are frequently used where natural drainage is inadequate and wet soils impair agricultural productivity (Jayakaran *et al.* 2005). Field tiles are perforated pipes installed just below the surface of the field to collect water and discharge it directly into the stream channel. The combination of tiling and channel straightening is beneficial to farmers but contributes to flashier flows and reduced in-channel habitat; such modifications are likely to impair stream communities and ecosystem function (Ward and Trimble 2004).

Traditional stream modification widens and straightens channels to increase the transport of water downstream and thereby contributes to draining of surrounding farmland. The regular occurrence of cycles of high and low flow results in episodes of erosion and re-deposition of sediments. During frequent low flows, sediment settles out of the water column and becomes deposited along the banks. Over time, sediment deposits may form benches along the stream banks which, if no maintenance and cleaning takes place, may further stabilize through the establishment of grasses (Landwehr and Rhoads 2003, Jayakaran *et al.* 2005). These grasses have the potential to take up nutrients and decrease sediment export during infrequent high flows (Kuhnle *et al.* 1999, Lyons *et al.* 2000, Landwehr and Rhoads 2003, Powell 2006). Because benches have been observed to develop naturally over time, the possibility exists that they may improve the ecological function of modified headwater streams. For this reason, and because of the potential benefits to water quality, an alternative channel design is now being considered as a potential best management practice (BMP). This BMP (grassed benches within the confines of the channel, bordering a narrow main channel) could be especially beneficial in areas where tiles discharge water directly into the channel, therefore limiting the opportunity for riparian buffer zones to improve surface water quality (Osborne and Kovacic 1993, Lyons *et al.* 2000).

The water quality of higher order streams depends in part on the energy supplies, processing of organic matter, and cycling of nutrients that occur in headwater streams (Alexander *et al.* 2000, Peterson *et al.* 2001). One way to evaluate the ecological functioning of headwater streams is through studying whole stream metabolism. Stream metabolism is a valuable ecological function to study because it is a measure of the biological activity of the system and influences the levels of organic matter processing and nutrient cycling (Roberts *et al.* 2007). Ecosystem metabolism is the net change in oxygen resulting from biological activity and is determined from rates of gross primary productivity (GPP) and ecosystem respiration (ER) (Bott 2006). Gross primary productivity is a measure of the rate of formation of organic matter through photosynthesis within an ecosystem; ecosystem respiration is a measure of the consumption or oxidation of all organic matter produced within the system (autochthonous energy sources) or supplied from outside the system (allochthonous energy sources) (Mulholland *et al.* 2001, Bott 2006).

Multiple environmental and water quality parameters have been shown to have an influence on rates of GPP and ER. Because autotrophs require light and nutrients for growth, photosynthetically active radiation (PAR) and concentrations of nutrients have been linked to rates of GPP (Elwood *et al.* 1981, Steinman 1992, Hill *et al.* 2001, Mulholland *et al.* 2001, Roberts *et al.* 2007). In addition to nutrients, heterotrophs also require a source of organic carbon. Concentrations of nutrients and organic matter have been shown to influence rates of ER (Elwood *et al.* 1981, Webster and Benfield 1986, Mulholland *et al.* 2001, Roberts *et al.* 2007). The majority of studies determining whole stream metabolism in headwater streams have concentrated on relatively undisturbed systems (Mulholland *et al.* 2001, Hall and Tank 2003, Houser *et al.* 2005, Ortiz-Zayas *et al.* 2005, Roberts *et al.* 2007). Very few studies have examined the effects of modifying headwater stream channels for agricultural drainage on stream metabolism (but see Bernot *et al.* 2006).

This study explores the impact of stream channel modification on the metabolic function of headwater streams in a highly agricultural landscape. First, I ask whether traditional trapezoidal-shaped drainage ditches and benched drainage ditches function similarly to natural (reference) headwater streams in terms of net daily metabolism. Second, I examine environmental and water quality variables that may influence the rates of gross primary productivity and ecosystem respiration in each type of headwater stream.

METHODS

Study Sites

This study focuses on headwater streams in and adjacent to the River Raisin watershed in southeastern Michigan (Figure 1). The River Raisin watershed is the most agricultural watershed in Michigan, with approximately 63% of the land cover categorized as agricultural (Dodge 1998, Cifaldi *et al.* 2004). As a result, many of the headwater streams in this area have been converted into agricultural drainage ditches by deepening, widening, and straightening natural headwater streams to ensure rapid downstream transport of water.

The sites used in this research were selected from a larger pool of 33 sites that had been previously studied by Janssen (2008). Janssen categorized each site according to its overall morphology into one of three categories: trapezoidal ditch, two-staged ditch (referred to as a benched ditch for this research), or reference stream. Trapezoidal ditches were characterized by overly-wide channels and lack of bench formation. Benched ditches had grassed benches within the confines of the channel, bordering a narrow main channel. Benching ratios were determined by Janssen (2008) using cross-sectional surveys, and were defined as the ratio of benched width to channel width in a given cross-section. This ratio was calculated by dividing the width of the benches by the width of the channel at a depth twice that of the bankfull depth of the narrow main channel (Figure 2). Benching ratios for the sites studied here were obtained directly from Janssen (2008) and ranged from 0.16 to 0.35. Reference streams included those that represented the most natural headwater stream conditions in the area. These sites generally contained more channel meandering and wooded riparian area, and were less likely to have subsurface tile entry points. The present study selected three study reaches, ranging from 65-70 meters in length, within each stream category. These study reaches were selected by visiting all 33 previously studied sites and subjectively choosing those that best represented each stream category. The width of the study reaches ranged from 0.5 to 5.0 meters and depth ranged from 0.1 to 0.5 meters (Table 1). Measurements of average width, average depth, wetted cross sectional area, average stream velocity and discharge, the percent of incident PAR reaching the stream surface, the percent of stream bottom covered by submerged vegetation, chlorophyll *a*, total phosphorus, nitrate, ammonia, total suspended solids, suspended organic matter, and the percent of organic matter in the sediment were collected from all nine sites in order to gain a clearer understanding of the differences among these stream categories. At three of the nine study sites (one from each stream category) additional data were collected including continuous readings of stream stage, dissolved oxygen, and water temperature in order to determine and evaluate differences in stream metabolism among stream categories. These three sites were selected because they represented the safest areas to leave equipment for long periods of time.

Stream Metabolism

Whole stream metabolism was determined using the open-system, single station diel dissolved oxygen change technique (Odum 1956, Bott 2006). Rates of gross primary productivity (GPP) and ecosystem respiration (ER) were determined from changes in dissolved oxygen (DO) *in situ.* Rates of gas exchange with the atmosphere (E) were calculated using oxygen reaeration coefficients (k_{O2}) determined by the Energy

Dissipation Model (Tsivoglou and Neal 1976). All rates were determined for three sites; one representing each stream category as described above.

Dissolved Oxygen and Temperature

Continuous DO and temperature measurements were obtained at 15-minute intervals using In Situ MP Troll 9000 Sondes equipped with optical dissolved oxygen sensors. Manufacturer calibrations were checked in the lab prior to deployment in the field using oxygen-free and oxygen-saturated water. Sondes were deployed at the center of each study reach approximately eight inches above the stream bottom and at an equal distance from each bank. DO and temperature were recorded at all three locations from 13-22 May 2008 and from 6 June – 1 July 2008. Barometric pressure was recorded once per week at each site using a Fisher Scientific handheld barometer and was also recorded continuously in the center of the study area with a Solinst Barologger (as described below). Pressure data from the handheld barometer was used along with *in situ* stream temperature data to determine percent saturation based on measured DO concentrations.

Velocity and Discharge

Stream velocity, depth, and width were measured at the top and bottom of each study reach once per week and used to calculate discharge. Top and bottom discharge values were averaged in order to obtain an average discharge for the study reach on the day of measurement. Cross-sectional area was calculated for the top and bottom of each reach from a series of width and depth measurements. Velocity for the top of the reach was determined by dividing discharge at the top of the reach by the cross-sectional area at the top of the reach. Velocity at the bottom of the reach was determined in the same manner. Top and bottom velocity values were averaged in order to obtain an average velocity for the study reach on the day of measurement. Average stream width was determined by measuring wetted width at ten equally spaced intervals along the reach. Stream stage was recorded every 15 minutes over the entire study period using Solinst Model 3001 Leveloggers placed at the center of each reach. Stage readings were corrected for barometric pressure using readings obtained from a Solinst Barologger located in the center of the study area. Average discharge and corresponding stage measurements were used to develop a relationship that allowed discharge to be determined from stage for every 15-minute interval. Average discharge was then used along with corresponding velocity measurements to develop a relationship that allowed velocity to be determined from discharge for every 15-minute interval.

<u>Oxygen Reaeration Coefficients</u>

In order to determine gas exchange with the atmosphere (E), reaeration coefficients (k_{O2}) were calculated at 15-minute intervals using the equation for the Energy Dissipation Model (Tsivoglou and Neal 1976):

$$k_{20^{\circ}C} = K' \cdot S \cdot V \qquad \text{(Eq. 1)}$$

where $k_{20^{\circ}C}$ is the oxygen reaeration coefficient at 20 ºC expressed in day^{-1}, S is the longitudinal slope of the reach in $m\ m^{-1}$, V is stream velocity in $m\ s^{-1}$, and K' is the oxygen diffusion coefficient and varies with stream discharge according to Table 2 (APHA 1998). Longitudinal slopes were obtained from cross-sectional surveys completed by Janssen (2008). Velocity and stream discharge were calculated at 15-minute intervals as described above. $k_{20^{\circ}C}$ was converted to min^{-1} and then adjusted for the actual stream temperature using the following equation (Bott 2006):

$$k_{O2(t^{\circ}C)} = k_{20^{\circ}C} \cdot 1.024^{(t^{\circ}C-20)} \qquad \text{(Eq. 2)}$$

This process resulted in the calculation of temperature-corrected oxygen reaeration coefficients for every 15-minute interval over the entire study period. Oxygen reaeration coefficients were then used along with dissolved oxygen and temperature readings to calculate continuous volumetric and areal rates of GPP, ER, and E (defined below).

Net Daily Metabolism

Daily rates of gross primary productivity (GPP) and ecosystem respiration (ER) were calculated for the study period using DO and temperature data recorded at 15-minute intervals (as in Houser *et al.* 2005 and Roberts *et al.* 2007). In this study, the rate of change in DO concentration was calculated as the difference between readings at 15-minute intervals. This rate of change is dependent upon GPP, ER and E, and can be used to calculate net daily metabolism based upon the following equation:

$$\Delta_{DO} = GPP - ER + E \qquad \text{(Eq. 3)}$$

Change in DO concentration, GPP, ER and E are volumetric rates between consecutive 15-minute measurements (expressed in g O_2 m^{-3} $hour^{-1}$).

Oxygen exchange with the atmosphere (E) was determined by multiplying the oxygen surplus or deficit (based on the difference between DO at 100% saturation with the atmosphere and the measured DO concentration in the stream water) at any given 15-minute interval by the corresponding temperature-corrected reaeration coefficient (k_{O2}):

$$E = (DO_{saturation} - DO_{observed}) \cdot k_{O2} \qquad \text{(Eq. 4)}$$

The change in oxygen due to metabolism (net metabolic flux) was obtained by subtracting E from the observed rate of DO change (Δ_{DO}).

Once corrected for atmospheric exchange, changes in DO concentration in the light are a result of the balance between GPP and ER while changes in DO concentration in the dark are due to ER alone. Daily ER was calculated by adding nighttime respiration to respiration during an interpolated photoperiod. Photoperiod respiration was determined by averaging respiration for the one hour intervals pre-dawn and post-dusk and extrapolating this value over the daylight hours (Mulholland *et al.* 2001, Houser *et al.* 2005, Roberts *et al.* 2007). GPP was determined as the difference between the photoperiod ER value and the net metabolic flux:

$$\text{GPP} = \text{net metabolic flux} - \text{photoperiod ER} \qquad \text{(Eq. 5)}$$

Volumetric rates of GPP and ER (g O_2 m^{-3} day^{-1}) were determined for each day of the study period by summing the 15-minute interval rates for each 24 hour period (00:00 to 24:00). Areal rates of GPP and ER (g O_2 m^{-2} day^{-1}) were calculated by multiplying mean stream depth by the volumetric rate. Net daily metabolism (NDM) is the net change of dissolved oxygen concentration per day resulting from biological activity and was calculated as the sum of GPP and ER (Bott 2006).

Photosynthetically Active Radiation

Photosynthetically active radiation (PAR) was recorded at all nine sites once per week. Cross-stream transects were set up at the top, middle, and bottom of the reach. Three measurements of PAR were taken along each transect at the surface of the stream (one at each bank and one in the center of the stream) using a LiCor LI-189 quantum photometer equipped with a LI-193SA spherical quantum sensor for a total of nine measurements per site per day. All nine recordings were used to get an average value of PAR reaching the stream surface for that day. A single measurement of PAR was also taken in an open area at each site prior to transect measurements in order to calculate the percentage of PAR reaching the stream surface. If cloud cover varied over the time spent at the site, a second measure of PAR was taken in the open and averaged with the first.

Submerged Vegetation

The percent of the stream bottom covered by submerged vegetation (submergent macrophytes or algal biomass) was determined from cross-stream transects at the top, middle, and bottom of each reach. At equally spaced intervals (20 or 50 cm depending on stream width), the presence or absence of submerged vegetation was recorded. Vegetation was considered absent if any part of the plant was emergent and thus able to release oxygen directly into the atmosphere.

Water Chemistry

Water quality samples were collected from all sites at the center of the reach once per week by directly submerging a one-liter polypropylene bottle. The bottle was rinsed three times before the final sample was captured. Samples were stored on ice in the dark until they were returned to the laboratory for processing. Fifty mL of sample were set aside in acid-cleaned Pyrex glass tubes and refrigerated for total phosphorus (TP) analysis at a later date. Approximately 12 mL of sample was filtered through a 0.2 µm nylon syringe filter and frozen for analysis of nitrite (NO_2^-) + nitrate (NO_3^-) (reported here as NO_3^-) and ammonia (NH_4^+). Nutrient concentrations were determined using standard automated colorimetric procedures on a Technicon Auto Analyzer II according to methods detailed in Davis and Simmons (1979). TP was determined by persulfate digestion after the method of Menzel and Corwin (1965), NO_2^- + NO_3^- by the cadmium reduction method based on the azo dye reaction, and NH_4^+ by the phenate method based on the indophenol blue reaction.

Chlorophyll *a*

Approximately 100 mL of sample was filtered through a Whatman GF/F filter for sestonic chlorophyll *a* analysis. Filters were placed in plastic tubes and frozen at -10 ºC for approximately two months until processing. Upon processing, frozen filters were allowed to thaw, 8 mL of acetone was added to each tube, and samples were sonicated for 20 minutes. Tubes were placed back in the freezer overnight for chlorophyll *a* extraction. Extract was analyzed fluorometerically the following day on a Turner Designs TD700 using the non-acidification method to determine chlorophyll *a* concentration.

Total Suspended Solids and Organic Matter

Total suspended solids concentrations were determined gravimetrically based on the weight of material retained on pre-weighed GF/F filters for known volumes of filtrate. Filters were dried at 60 ºC for 24 hours to obtain dry weight and a measure of total suspended solids. Filters were then combusted at 450 ºC for 4 hours to obtain a combusted weight and a measure of suspended organic matter.

Stream sediments generally consisted of a layer of silt over clay. The organic content of the sediment was determined 1-2 times for each site over the course of the study period. At each site, four samples of approximately 30 mL were taken by hand from the top four centimeters of sediment near the center of the reach using a metal scoop. Each sample was dried at 60 ºC for 24 hours to obtain the dry weight and then combusted at 450 ºC for 4 hours. After combustion, the proportion of organic matter in the sediment was determined for each sample based on weight loss. Values were averaged for each site to determine the organic content of the stream sediment.

Data Analysis

In order to assess differences in environmental variables among all nine study sites, values were averaged over time for each site so that three replicates existed in each stream category. Analysis of Variance (ANOVA; SPSS version 14.0) tests were performed based on stream category to see if there were significant differences in means of environmental variables among stream categories. If variation among stream categories was greater than 20-fold for any one parameter, values for that parameter were normalized through log-transformation (as in Mulholland *et al.* 2001). If a significant difference among stream categories was detected, a post-hoc multiple comparisons test (Tukey test) was performed in order to test all pairwise comparisons of means.

Similarly, ANOVA tests were performed for the three metabolism sites to detect differences in means of parameters. In this case, means for each site were determined by averaging daily measurements taken over the 6 week study period. Again, data were log-transformed if the variance among stream categories was greater than 20-fold, and a Tukey test was performed following a significant ANOVA.

Correlation analysis was used to identify relationships between single environmental variables and metabolism rates (rates of gross primary productivity and rates of ecosystem respiration). Correlations were performed in order to determine how these relationships differed among metabolism sites and were assessed using Pearson correlation coefficients (r) with a significance level of $\alpha = 0.05$.

RESULTS

Ecological Comparison of Nine Study Sites

Comparing across stream categories, the average percentage of incident PAR reaching the stream surface was slightly higher at benched and trapezoidal sites than at reference sites (Table 1). No significant difference among means was detected. Shading of the stream could be attributed to an abundance of over-hanging grasses at benched sites, moderate riparian vegetation (grasses and small shrubs) at trapezoidal sites, and the presence of woody riparian vegetation at all reference sites (personal observation).

On average, benched sites had a very high percentage of the stream bottom covered by submerged vegetation (76.5%), compared with 34.3% for trapezoidal sites and 7.8% for reference sites (Table 1). The mean for benched sites was significantly higher than the mean for reference sites ($p = 0.007$) but not significantly higher than the mean for trapezoidal sites.

On average, total phosphorus was nearly equal at benched and trapezoidal sites and was slightly higher at reference sites. NO_3 was, on average, highest at trapezoidal sites, intermediate at benched sites, and lowest at reference sites. Concentrations of NH_4 were highest, on average, at reference sites and lower at the trapezoidal and benched sites (Table 1). No significant difference existed among means for stream categories for any water chemistry measurements.

Mean chlorophyll *a* concentrations did not differ significantly among stream categories but tended to be highest at benched sites, intermediate at reference sites, and lowest at trapezoidal sites (Table 1).

Average total suspended solids concentrations were higher at trapezoidal and reference sites than at benched sites. Concentrations of suspended organic matter were similar at reference and trapezoidal sites and lower at benched sites. The average percentage of organic matter in the sediments was highest at benched sites and similar at trapezoidal and reference sites (Table 1). Mean values did not differ significantly among stream categories for total suspended solids, suspended organic matter, or the percentage of organic matter in the stream sediments.

Overall, environmental and water quality variables for all nine sites provide little basis for distinguishing among the three stream categories. Only the mean percent of stream bottom covered by submerged vegetation differed significantly among stream categories; benched sites had significantly more submerged vegetation than reference sites, $p = 0.007$.

Stream Metabolism Sites

The three sites selected for metabolism comparisons, representing one of each stream category, differed from one another to a greater degree for some variables than was observed when all nine sites were compared (see Table 3 for summary of ANOVA statistical results). The highest percentage of incident PAR reached the stream surface at the trapezoidal site (82%), compared with a slightly lower value for the benched site (68%), and a much lower value for the reference site (23.6%). This pattern was consistent with the pattern found for all nine sites. PAR means differed significantly between the reference site and both the trapezoidal ($p < 0.005$) and the benched site ($p = 0.001$), but not between the benched and trapezoidal sites. All sites showed a general decline in the percentage of sun reaching the stream surface over the sampling period (Table 4).

The benched site had an abundant amount of submerged vegetation (89.4% of stream bottom covered), compared with minimal amounts at the trapezoidal (11.7%) and reference site (less than 1%) (Table 4). This pattern was also observed when all nine sites were compared. Vegetation coverage was significantly greater at the benched site than the other two sites ($p < 0.005$), which did not differ from one another.

Average concentrations of TP were slightly higher at the benched site and similar at the trapezoidal and reference sites which is opposite of what was observed for all nine sites. No significant differences in mean TP concentrations were detected among sites. The average NO_3 concentration was 2.9 mg L^{-1} at the trapezoidal site, 0.9 mg L^{-1} at the benched site, and 0.2 mg L^{-1} at the reference site which was the same pattern observed when all nine sites were compared. After transformation, the log NO_3 concentration at the trapezoidal site was significantly higher than the log NO_3 concentration at the benched site ($p = 0.024$) and at the reference site ($p < 0.005$). The log NO_3 concentration at the benched site was also significantly higher than the concentration at the reference site ($p = 0.009$). Average concentrations of NH_4 were highest at the trapezoidal site most likely due to one day that was an outlier, and similar at the benched and reference sites (Table 4). No significant difference existed among means for concentrations of NH_4.

Mean chlorophyll *a* concentrations did not differ significantly among metabolism sites. The average chlorophyll *a* concentration was highest at the benched site (similar to what was observed with all nine sites) and was most likely skewed up due to an outlier. Average concentrations were moderately lower at the reference and trapezoidal sites (Table 4).

Average total suspended solids were highest at the reference site (28.7 mg L^{-1}), intermediate at the trapezoidal site (14.6 mg L^{-1}), and lowest at the benched site (7.5 mg L^{-1}). The mean concentration of total suspended solids at the reference site was significantly higher than the mean at the benched site ($p = 0.033$) but not significantly higher than the mean at the trapezoidal site. Average concentrations of suspended organic matter were equal at the benched and trapezoidal sites and highest at the reference site. All three metabolism sites had nearly equal percentages of organic matter in the sediment (Table 4). The means for metabolism sites did not differ significantly for organic suspended matter. Statistical analyses could not be performed on the percentages of organic matter in the stream sediment because data were only collected once over the study period.

A clearer division exists among stream categories for some environmental and water quality variables when only the metabolism sites are considered. Means differed significantly between two or more stream categories for the percent of incident PAR reaching the stream surface, the percent of stream bottom covered by submerged vegetation, concentrations of NO_3, and concentrations of total suspended solids (Table 3).

Stream Metabolism

<u>Dissolved Oxygen and Temperature</u>

Patterns in diel dissolved oxygen concentrations developed from sonde measurements obtained at 15-minute intervals differed among metabolism sites throughout the study period. Typical patterns observed at each site are shown here using dissolved oxygen curves for three representative days in June 2008 (Figures 3-5). These dates were chosen to represent patterns at the site because they displayed rates of GPP, ER, and NDM similar to the average for the site over the study period.

Very small day to night variation in dissolved oxygen was observed at the reference site, where DO levels ranged from near 7.5 mg O_2 L^{-1} at night to around 8.3 mg O_2 L^{-1} during the day over 14-16 June 2008 (Figure 3). Moderate diel swings were observed at the trapezoidal site where DO levels dropped to about 8 mg O_2 L^{-1} during the night and increased to around 11 mg O_2 L^{-1} during the day over 15-17 June 2008 (Figure 4). Very large diel changes were observed at the benched site where DO levels fell to between 0 and 3 mg O_2 L^{-1} at night and reached between 20 and 28 mg O_2 L^{-1} during the day over 10-12 June 2008 (Figure 5).

<u>Velocity and Discharge</u>

Calculation of continuous k_{O2} using the Energy Dissipation Model (Eq. 1) required continuous measurements of velocity and discharge, which were estimated from stream stage measurements recorded every 15 minutes at all three metabolism sites. The modeled relationships using stage (*s in meters)* and corresponding discharge (*Q in L* sec^{-1}*)* measurements at each site were:

$$\text{Reference: } Q = s^{\,2.2935} \cdot 10^{\,3.4491} \quad (r^2 = 0.99)$$

$$\text{Trapezoidal: } Q = s^{3.6871} \cdot 10^{3.7955} \quad (r^2 = 0.99)$$

$$\text{Benched: } Q = s^{3.6971} \cdot 10^{2.9746} \quad (r^2 = 0.66)$$

Following determination of continuous discharge, the relationship between discharge (*Q in L sec*$^{-1}$) and velocity (*V in m min*$^{-1}$) was found to be estimated by:

$$\text{Reference: } V = (0.0004 \cdot Q) + 0.0935 \quad (r^2 = 0.97)$$

$$\text{Trapezoidal: } V = (0.0009 \cdot Q) + 0.0443 \quad (r^2 = 0.99)$$

$$\text{Benched: } V = (0.0017 \cdot Q) + 0.0128 \quad (r^2 = 0.91)$$

Average discharge was very low at the benched metabolism site (25.2 L s^{-1}), moderate at the trapezoidal site (112.3 L s^{-1}), and highest at the reference site (311.9 L s^{-1}) (Table 4). The high average discharge at the reference site was most likely influenced by measurements taken during two weeks when water levels were high due to localized storms. After transformation, the log *Q* at the reference site was significantly higher than log *Q* at the benched site ($p < 0.005$). Log *Q* at the trapezoidal site was also significantly higher than log *Q* at the benched site ($p = 0.004$), but the reference and trapezoidal sites did not differ significantly (Table 3). Average velocity showed a similar pattern; highest at the reference site (12.8 m min^{-1}) and lowest at the benched site (3.3 m min^{-1}) (Table 4). Mean velocity at the reference site was significantly higher than mean velocity at the benched site ($p = 0.003$) (Table 3).

Oxygen Reaeration Coefficients

Using estimates of continuous velocity and discharge, oxygen reaeration coefficients (k_{O2}) were determined for every 15-minute interval using the EDM (Eq. 1) and then adjusted for stream temperature (Eq. 2). The average k_{O2} was highest at the reference site (0.0115 min^{-1}), intermediate at the trapezoidal site (0.0081 min^{-1}), and lowest at the benched site (0.0034 min^{-1}) (Table 5). The mean k_{O2} at the reference site was significantly higher than at the trapezoidal and benched sites ($p < 0.005$); in addition the trapezoidal site differed significantly from the benched site ($p < 0.005$) (Table 3).

Net Daily Metabolism

The change in oxygen due to metabolism (net metabolic flux) for each site was obtained by subtracting the oxygen exchange with the atmosphere (E) from the observed rate of DO change. The net metabolic flux at the reference site was always below zero (Figure 6), indicating that this reach consistently consumed more oxygen than it produced on a diel basis. Ecosystem respiration was, on average, five times greater than gross primary productivity for the reference reach (-5.44 g O_2 m^{-2} day^{-1} and 0.92 g O_2 m^{-2} day^{-1}, respectively). The average P:R ratio (0.16) and net daily metabolism (-4.52 g O_2 m^{-2} day^{-1}) indicate a very heterotrophic system (Table 5).

During the daytime, the trapezoidal site produced more oxygen than it consumed and there was a net flux of oxygen into the system from primary producers (Figure 7). However, on a diel basis, ecosystem respiration was approximately twice as large as gross primary productivity (-4.99 g O_2 m^{-2} day^{-1} and 2.02 g O_2 m^{-2} day^{-1}, respectively), thus this system consumed more oxygen than it produced. The average P:R ratio (0.48) and net daily metabolism (-2.97 g O_2 m^{-2} day^{-1}) signify a heterotrophic system (Table 5), although less so than the reference reach.

An abundance of oxygen was produced via gross primary production at the benched metabolism site during the day (Figure 8). On average, gross primary productivity (12.11 g O_2 m^{-2} day^{-1}) was greater than ecosystem respiration (-11.05 g O_2 m^{-2} day^{-1}) and consequently this system produced more oxygen than it consumed. The average P:R ratio (1.10) and net daily metabolism (1.06 g O_2 m^{-2} day^{-1}) both point towards autotrophy (Table 5).

Correlation Analysis

Measures of ecosystem metabolism correlated with a number of environmental variables depending upon site and stream type (see Tables D-F in appendix for full correlation matrices). At the reference site, daily rates of GPP were positively correlated with chlorophyll *a* concentrations ($r = 0.851$, $p = 0.034$) and negatively correlated with NO_3 ($r = -0.992$, $p < 0.005$) (Table 6). Rates of ER were positively correlated with chlorophyll *a* concentrations ($r = 0.900$, $p = 0.019$) and the percentage of incident PAR reaching the stream surface ($r = 0.877$, $p = 0.025$), and marginally positively correlated with concentrations of suspended organic matter ($r = 0.794$, $p = 0.054$) (Table 6).

At the trapezoidal site, rates of GPP were positively correlated with TP ($r = 0.966$, $p = 0.004$), NO_3 ($r = 0.878$, $p = 0.025$), organic suspended matter ($r = 0.864$, $p = 0.030$), and NH_4 ($r = 0.816$, $p = 0.046$) (Table 6). Daily rates of ER were positively correlated with concentrations of organic suspended matter ($r = 0.877$, $p = 0.025$) and NO_3 ($r = 0.804$, $p = 0.050$), marginally positively correlated with NH_4 ($r = 0.776$, $p = 0.061$) and TP ($r = 0.698$, $p = 0.095$), and marginally negatively correlated with the percent of stream bottom covered by submerged vegetation ($r = -0.858$, $p = 0.071$) (Table 6).

Daily rates of GPP at the benched site were positively correlated with NH_4 ($r = 0.928$, $p = 0.004$), NO_3 ($r = 0.814$, $p = 0.024$), and marginally positively correlated with TP ($r = 0.614$, $p = 0.097$) (Table 6). Rates of ER were also positively correlated with

NH_4 ($r = 0.872$, $p = 0.012$), NO_3 ($r = 0.875$, $p = 0.011$), and TP ($r = 0.774$, $p = 0.035$) (Table 6).

Results from correlations between GPP and ER for each metabolism site indicate that GPP and ER were not well correlated at the reference ($r = 0.589$, $p = 0.148$) or trapezoidal sites ($r = 0.580$, $p = 0.153$), but were significantly positively correlated at the benched site ($r = 0.940$, $p = 0.003$) (Table 6).

DISCUSSION

Straightened and channelized streams, common throughout low-lying agricultural land in many parts of the world, lack complex habitat (Herricks 1996, Frothingham *et al.* 2002), support primarily a simplified and tolerant biota (Wang *et al.* 2001, Janssen 2008), and are generally assumed to have altered function (Ward and Trimble 2004). Although direct studies of ecosystem function in agricultural drainage ditches are few, the lack of complex habitat within the channel and reduced water residence time make it likely that biological processing of organic matter and nutrients are reduced relative to natural systems. Recently, the benched ditch with its in-channel floodplain has been proposed as a BMP that may help to restore some beneficial ecosystem functions (Powell 2006). My study, one of the first to test this proposition, found that rates of net daily metabolism were most similar in trapezoidal ditches and reference streams, but that trapezoidal ditches and benched ditches were more directly comparable in terms of overall ecosystem function due to the impacts of agricultural activities on these systems. I found that nutrients (NO_3, NH_4, and TP) were positively correlated with rates of GPP and ER at both the trapezoidal and benched ditches, suspended organic matter was positively correlated with rates at the trapezoidal ditch and reference stream, and chlorophyll *a* and the percent of incident PAR reaching the stream surface were positively correlated with rates at the reference stream.

Metabolism Patterns in each Stream Type

Reference Reach

Rates of GPP were low at the reference site presumably due to light limitation of autotrophic activity. The pattern of net daily metabolism at the reference reach suggested a strong influence of riparian shade on stream autotrophs and hence on GPP. Productivity was highest in mid to late May 2008, decreased to almost zero on 10 June 2008, and then increased again on 11 June 2008 but only to rates about half those in May (Table 7). The percent of incident PAR reaching the stream surface was also highest at the beginning of the study period and decreased over time (Table 4). The progression of bare trees to leaf-out in the forested riparian of the reference reach resulted in the stimulation of autotrophic productivity in spring and a decrease in productivity as light became limiting. Multiple studies have found evidence that riparian vegetation is an important determinant of light availability and consequently of gross primary productivity (Bott *et al.* 1985, Young and Huryn 1999, Lyons *et al.* 2000, Mulholland *et al.* 2000, 2001; Roberts *et al.* 2007).

Although very little submerged vegetation was observed at the reference site (the percent of the stream bottom covered by submergent macrophytes or algal biomass remained minimal throughout the study period), a positive correlation between rates of

GPP and concentrations of water column chlorophyll *a* suggests that algae in the water column responded to changes in light.

Continuously low concentrations of NO_3 suggest that the reference stream was likely least influenced by agricultural practices and may have had the greatest potential for nutrient removal. Concentrations of NO_3 were relatively low at the reference site and remained low throughout the summer (Table 4). This reach was selected as a reference site because it represented the most natural headwater stream conditions in the area and was least likely to have subsurface tile entry points. Therefore, low NO_3 concentrations may be attributed to fewer direct inputs of nitrate sources due to less tile drainage. In addition, the forested riparian zone at this site may have created conditions suitable for nitrate uptake. Multiple studies have credited nutrient removal to forested riparian buffers (Lowrance *et al.* 1984, Peterjohn and Correll 1984, Lyons *et al.* 2000).

At the reference site, ER and GPP were influenced by some of the same environmental factors, and therefore at least a portion of ER derived from autotrophic respiration. Similar to patterns observed for GPP, concentrations of chlorophyll *a* and the percent of incident PAR reaching the stream surface were positively correlated with rates of ER. This was surprising considering that ER rates were five times greater than GPP (Table 7) and that heterotrophic respiration was presumed to play a large role in this system. Possibly, these correlations indicate that the proportion of respiration due to autotrophs declined as light levels decreased.

Concentrations of suspended organic matter were also positively correlated with rates of ER. Roberts *et al.* (2007) found that when high rates of GPP corresponded with high rates of ER, primary producers were likely supplying organic matter to fuel autotrophic and heterotrophic respiration. Because autotrophic productivity was low and was not correlated with suspended organic matter in this study, little evidence exists to support the conclusion that concentrations of suspended organic matter were a result of primary productivity and contributed to significant levels of autotrophic or heterotrophic respiration. However, the positive correlation between ER and suspended organic matter could indicate that allochthonous sources of organic matter fueled heterotrophic respiration and that the majority of suspended organic matter was coming from outside the reach. Roberts *et al.* (2007) found an increase in microbial heterotrophic respiration with an increase in availability of labile organic matter. Similarly to what was believed to be occurring at the reference site, Iwata *et al.* (2007) found that the effects of allochthonous organic matter inputs on heterotrophic respiration overwhelmed autotrophic production in systems that were light limited.

Concentrations of TP, NH_4, total suspended solids, and suspended organic matter showed an increase near 11 June 2008, the same date that GPP decreased to almost zero (Table 4 and Table 7). Examination of the hydrograph reveals that discharge increased about 3-fold on this day due to a storm that covered the study area (Figure 9). Uehlinger (2006) and Roberts *et al.* (2007) showed that increases in discharge due to storm events resulted in an immediate and extended reduction in GPP due to loss of autotrophic biomass and increased turbidity. However, those studies also showed a short-term decrease in ER on the day of peak discharge as a result of the reduction in autotrophic respiration. This pattern was not observed for ER in this system, most likely because the majority of ER was coming from heterotrophic rather than autotrophic respiration.

The findings at the reference site suggest that light limited rates of GPP in this system. ER also responded to a decrease in light availability suggesting that the portion of ER due to autotrophic respiration decreased with a decrease in light. Because ER was five times greater than GPP in this system, heterotrophic respiration must have played a large role. The positive correlation between rates of ER and suspended organic matter is further evidence that allochthonous energy inputs fueled heterotrophic respiration. Rates of GPP and ER were not significantly correlated with each other in the reference reach. This indicates that the majority of ER was due to heterotrophic respiration and was not surprising for a small, well-shaded stream that was highly net heterotrophic.

Trapezoidal Reach

Higher light levels and a slight increase in submerged vegetation compared with the reference site likely resulted in higher rates of GPP at the trapezoidal site. Rates of GPP remained about the same over the study period except for one day when rates doubled (9 June 2008) (Table 8). Because the site had very little riparian vegetation, the percent of incident PAR reaching the stream surface was highest at this site and remained at high levels throughout the study period (Table 4). Although this site had the highest percentage of sunlight reaching the stream, macrophytic and algal biomass was still fairly low (on average, only 11% of the stream bottom was covered by submerged vegetation) (Table 4). It is difficult to determine why autotrophic production remained minimal even though light did not appear to be a limiting factor. One possible explanation for this is the frequency at which traditional trapezoidal systems undergo maintenance. Agricultural drainage ditches are traditionally maintained through regular clearing of sediment and vegetation. Maintenance may have been performed at this site in recent years and could have resulted in the removal of established photosynthetic biomass.

GPP and ER showed similar patterns over time at the trapezoidal site (Table 8) and correlations indicated that some of the same environmental and water quality parameters that influenced GPP also influenced ER (Table 6). Nutrient enrichment has been shown to stimulate heterotrophic respiration by increasing autotrophic productivity in multiple studies of whole stream metabolism (Meyer and Johnson 1983, Suberkropp and Chauvet 1995). Because both rates were positively correlated with nutrient concentrations (TP, NO_3, NH_4) at the trapezoidal site, we can assume that a moderate portion of ER came from autotrophic respiration and that the increase in autotrophic productivity in-part fueled heterotrophic respiration.

Autotrophic productivity was likely contributing to concentrations of autochthonous organic matter in the water column and fueling autotrophic and heterotrophic respiration because, unlike at the reference site, both GPP and ER were positively correlated with concentrations of suspended organic matter. However, additional organic matter must have also been coming from allochthonous sources because there was an increase in concentrations with an increase in discharge (Table 4).

Concentrations of nutrients, total suspended solids, and suspended organic matter increased on the same day that storm discharge increased (Table 4 and Figure 10). One difference observed between the reference site and the trapezoidal site was that concentrations of NO_3 increased with discharge at this site, whereas at the reference site NO_3 concentrations remained the same throughout the storm event (Table 4). This suggests that perhaps the reference site was less impacted by agricultural practices than was the trapezoidal site. A study by Johnson *et al.* (1997) linked high proportions of agricultural land use to increased stream concentrations of NO_3. Unlike at the reference site, rates of GPP increased with an increase in discharge (Table 8 and Figure 10). Most studies, and observations at the reference site, show that rates of GPP decrease with an increase in discharge following a storm event. Although some in-stream light limitation most likely occurred with the storm (concentrations of total suspended solids increased), perhaps the increase in discharge delivered a pulse of a limiting nutrient from the catchment which was large enough to stimulate GPP despite lower in-stream light levels.

Light was not presumed to be a limiting factor at the trapezoidal site. However, drain maintenance activities in recent years may have decreased levels of photosynthetic biomass resulting in minimal rates of GPP. Compared to the reference site, average rates of ER were only twice those of GPP. Positive correlations between rates of metabolism and TP, NH_4, and NO_3 indicate that nutrients were stimulating autotrophic productivity and subsequently autotrophic respiration. However, rates of GPP and ER were not significantly correlated with each other in the trapezoidal reach and therefore we can conclude that the majority of ER was due to heterotrophic respiration.

<u>Benched Reach</u>

High light levels, in addition to limited channel maintenance and high concentrations of nutrients, resulted in very high macrophytic and algal biomass and therefore high rates of GPP at the benched site. Rates of GPP were moderately high throughout the study period except for a week in mid-June 2008 when rates doubled (GPP was at its maximum on 11 June 2008) (Table 9). The percent of incident PAR reaching the stream surface was very high at the beginning of the study period, but decreased as grasses grew along the benches (Table 4). Although shading did occur over time, the percent of incident PAR reaching the stream surface was still 55% at the end of the study period making it unlikely that this site became light limited. The percent of the stream bottom covered by submerged vegetation was initially high (60%) and increased to near 100% as the summer progressed (Table 4). A lack of recurrent maintenance can result in bench formation over time in modified drainage ditches. Because benches were present at this site, we can assume that this site most likely had not undergone recent maintenance, which may have contributed to significantly higher levels of submerged vegetation at this site versus at the trapezoidal site that had similar light levels.

Because nutrients were not limiting in this system, high levels of autotrophic productivity occurred, resulting in high rates of GPP. Although the amount of light reaching the stream surface decreased over time, an increase in submerged vegetation was observed (Table 4). Water nutrients remained at fairly high concentrations throughout the summer and so it is likely that macrophytic and algal biomass increased in response to these consistently high levels of nutrients.

The same factors that influenced GPP also influenced ER at the benched site. Rates of ER followed the same pattern over time as did rates of GPP (Table 9) and both were positively correlated with the same nutrients (NH_4, NO_3, and TP). Because ER mirrored GPP, we can assume that the majority of ER was due to autotrophs (either directly through autotrophic respiration or indirectly by autotrophs providing labile organic matter for heterotrophic consumption). At this site, nutrients supported high levels of submerged vegetation and therefore high rates of gross primary productivity.

High rates of GPP resulted in high rates of autotrophic respiration and consequently high rates of ER.

Rates of GPP and ER doubled in early to mid June 2008 (Table 9). This increase was peculiar because light levels were decreasing over time. If it were due to increased macrophyte or algal biomass alone, one would expect rates to remain high since levels of submerged vegetation remained high through the end of the study period (Table 4). However, rates of GPP and ER decreased again to levels similar to those near the beginning of the study period. The only environmental parameters that fit the same pattern are concentrations of TP and NH_4, and therefore we can assume that an increase in these nutrients stimulated additional productivity.

Benching provided a beneficial opportunity to reduce sediment export to downstream water bodies. Concentrations of total suspended solids and suspended organic matter did not show large increases with the storm event (Table 4). A study of the benefits of a grassed riparian zone in agricultural landscapes found that grassy riparian zones had more limited inputs of organic matter to streams than those with a forested riparian (Lyons *et al.* 2000).

In contrast to the reference and trapezoidal sites, the benched site was net autotrophic. This autotrophy can be attributed to high levels of macrophytic and algal biomass, which were a result of high light levels and a lack of drainage maintenance. GPP and ER were both positively correlated with concentrations of NH_4, NO_3, and TP suggesting that nutrients may have been fueling primary productivity and that the majority of ER at this site was coming from autotrophic respiration. This is further supported by the fact that rates of GPP were significantly positively correlated with rates of ER. It appears that neither light nor nutrients were limiting in this system.

Ecosystem Function

Headwater streams are important sites for the removal and retention of nutrients and for sediment reduction and storage because they collect water directly from land and transport it to downstream aquatic systems (Alexander *et al.* 2000, Peterson *et al.* 2001, Powell 2006). However, modification of headwater streams through subsurface drainage and channelization in areas of intensive agriculture has reduced these potential benefits to water quality and has altered stream ecosystem function. Subsurface drainage has increased the rate at which water and nutrients are delivered from land to streams (Skaggs and Chescheir 2003). Even if riparian buffer zones are present, much of the water leaving agricultural land modified with subsurface drainage bypasses these areas, therefore minimizing the potential for the buffer to improve water quality (Powell 2006). Channelization has reduced water residence time in headwater streams resulting in systems that are less efficient at retaining and removing nutrients and storing sediments. In this study of agricultural headwater streams, I found that the reference stream was likely least influenced by agricultural practices and perhaps had the greatest potential for nitrate uptake. However, it is probable that modified channels lacking a forested riparian zone (both trapezoidal and benched in shape) occur more frequently in agricultural landscapes. Below, I discuss the potential impacts of both of these channel shapes on the ecological functioning of the system.

Forested headwater streams are generally heterotrophic because riparian vegetation limits the light available for primary producers and large inputs of allochthonous organic matter provide basal resources for heterotrophic respiration (Mulholland *et al.* 2001, Roberts *et al.* 2007). My measurements of net daily metabolism for the reference stream supported these findings. The biological activity associated with primary productivity is responsible for the uptake of nutrients and can improve subsurface and surface water quality. Although very little productivity occurred within the reference reach, the stream was located in a forested riparian zone and so was subject to the benefits that riparian zones provide for the retention of nutrients. Peterjohn and Correll (1984) found that plant growth and denitrification in a forested riparian buffer were responsible for the retention and removal of nutrients leaving an agricultural watershed. Riparian forests can also be beneficial for water quality through the removal of subsurface nitrate (Lowrance *et al.* 1984) and by assimilating nitrogen from runoff (Lyons *et al.* 2000). Forested riparian zones provide the advantage of long-term storage or removal of these nutrients. I observed low concentrations of nitrate over the entire study period and attributed it to fewer direct inputs of nutrients but also to nutrient removal by the forested riparian zone. Forested riparian zones, however, can be susceptible to erosion. Lyons *et al.* (2000) found that shading reduced understory vegetation and resulted in areas of bare soil with high erosion potential. Although some sediment was likely coming from upstream, this pattern of erosion could have been occurring at my reference site and may have been responsible for the high concentrations of suspended solids at this site. The fact that this site had a forested riparian zone distinguished it from the other two metabolism sites in this study. The forested riparian resulted in minimal in-stream productivity but was likely responsible for nutrient removal from surface and subsurface water. The forested riparian zone set this site apart from the open, channelized systems that are predominant in agricultural areas.

Although a riparian forest buffer is beneficial for the long-term removal of nutrients from stream ecosystems, it is likely that channels lacking a forested riparian zone occur more frequently in agricultural landscapes. Traditionally, these modified streams have been associated with multiple adverse impacts on water quality and consequently on ecosystem function. Studies have found that trapezoidal systems can be sources of suspended sediment due to erosion during high flows, bank failures, and maintenance practices (Trimble 1997, Simon *et al.* 2000). Because connectivity between the stream channel and the floodplain is greatly reduced in trapezoidal systems (Jayakaran *et al.* 2005), little opportunity exists for sediments to be removed during periods of high flow. Frequent maintenance results in the removal of sediment and in-stream vegetation and therefore limits the potential for the uptake of nutrients through primary productivity. Although higher levels of productivity occurred at my trapezoidal site than at my reference site, productivity was still minimal and provided little opportunity for nutrient retention in a system that was more impacted by agricultural activities. The efficiency of nutrient retention and removal can be expected to decrease as water residence time decreases. Royer *et al.* (2004) suggested that in channelized streams, nutrient inputs to the stream are exported quickly and may only be retained in late summer when stream flows are low. Although the average wetted cross sectional area of my trapezoidal site was very similar to that of my benched site, the average velocity in the trapezoidal site was approximately three times greater than the average velocity for the benched site (Table 4). Minimal stream bank and in-stream vegetation in the trapezoidal site make nutrient retention and removal difficult. Channelization has created a situation where water residence time is shortened, limiting the capacity for nutrient and organic matter cycling. For these reasons, trapezoidal systems are least likely to improve ecosystem functioning in agricultural areas.

Benched ditches may be a better alternative to traditional trapezoidal ditches in agricultural areas where drainage is still preferred but where improvements in water quality and ecosystem function are desired. Landwehr and Rhoads (2003) concluded that the benched ditch allows a stable channel to be developed within the system while still meeting the drainage function of a ditch. Benching can facilitate water quality improvements similar to those obtained with floodplains by acting as in-channel floodplains in areas were subsurface drainage delivers a majority of the water directly to the channel (Powell 2006). Multiple studies found that grasses and dense vegetation on benches enhanced the deposition and storage of sediments by slowing the flow of water (Lyons *et al.* 2000, Landwehr and Rhoads 2003, Powell 2006). Grasses also have the potential to stabilize stream banks and decrease associated erosion (Peterson 1993, Dunway *et al.* 1994, Lyons *et al.* 2000, Powell 2006). In my benched reach, I observed significantly lower concentrations of total suspended solids and attributed it to the benefit of the grassed benches. Bench vegetation provides the additional advantage of nutrient retention through plant uptake and nitrogen removal through denitrification, both of which are unlikely to occur in trapezoidal ditches that lack vegetation (Bernot and Dodds 2005, Powell 2006). Nutrients, especially phosphorus which has a high affinity to soil particles, can be stored in the sediment that becomes deposited on benches (Powell

2006). The impact of benching on nutrient retention and storage has been studied by others but the potential for nutrient retention in my system is less clear. Although the positive correlations I observed between rates of metabolism and nutrients in my benched system implied that biological activity was in part dependant upon nutrient concentrations, I did not specifically measure the nutrient removal capacity of the system. A study by Mulholland *et al.* (2008) revealed that the uptake efficiency relative to availability of nitrate increased with increased rates of GPP. I observed very high rates of GPP in my benched reach suggesting that the uptake efficiency in this system was high and that the macrophytic and algal biomass present was important for nitrate removal. Although the presence of vegetation on benches and in the channel makes nutrient retention more likely, this benefit may only be temporary. Peterson *et al.* (2001) and Royer *et al.* (2004) cautioned that uptake by plants in agricultural streams only represents short-term storage and that accumulated nutrients and organic matter are likely to be exported within weeks to several years. Even though benched ditches have the potential to provide beneficial ecosystem services and improve water quality, there are some undesirable consequences associated with the abundance of vegetation in these systems. I observed concentrations of DO lower than 1 mg L^{-1} at night in my benched system. Schlosser and Karr (1981) and Wiley *et al.* (1990) found that declines in nighttime DO due to excessive vegetation resulted in decreases in desirable fish and invertebrate populations. However, in a study of the same agricultural streams researched here, Janssen (2008) found little difference in the biotic communities between drains (trapezoidal and benched) and reference streams. Vegetation facilitates the retention of nutrients and allows for decreases in the stream sediment load in benched ditches.

Although the abundance of vegetation in my benched system resulted in low levels of DO at night, it provided greater opportunity for improvements in ecosystem function than did the trapezoidal site.

Conclusions

Headwater streams in agricultural landscapes are traditionally modified to improve conditions for agriculture. This modification alters ecosystem function and has detrimental impacts on downstream water bodies. In this study, I evaluated the impact of channel modification on the biological activity of these headwater streams by comparing net daily metabolism in reference streams, trapezoidal drainage ditches, and benched drainage ditches. I found that the metabolism and ecosystem functioning occurring in reference streams was not directly comparable to trapezoidal and benched drainage ditches because drainage ditches were located in open systems that were heavily influenced by agriculture while the reference stream was located in a forested riparian and was likely less impacted by agricultural activities. When I compared a channelized trapezoidal system to a benched system, I found that that the benched system had a greater capacity for nutrient uptake and suspended sediment reduction and therefore provided more opportunities for improved water quality and ecological functioning.

Because metabolism measurements were performed at only three sites, it is difficult to extrapolate my results to include drainage ditches throughout the Midwest. Nine study sites were initially selected for this study, but due to equipment limitations, metabolism was only measured at three. Only environmental and water quality parameters were measured at the remaining six. When differences among stream categories were determined using environmental and water quality data from all nine sites, stream categories were less distinguishable. Future metabolism work in these systems should incorporate additional sites in order to better understand the patterns of net daily metabolism occurring in each type of agricultural drainage system.

The work presented in this study was conducted in the spring and summer months when these systems were likely most productive. It would be interesting to observe how metabolism patterns change at these sites over the fall and winter months. Perhaps the benched site is only autotrophic during the short productive growing season, after which respiration dominates. Since in-stream vegetation only provides temporary retention of nutrients, it would also be beneficial to look at patterns in water quality throughout the year (specifically during fall senescence) to determine the impact that seasonal storage of nutrients may have on downstream water bodies.

My study is one of the first to directly evaluate ecosystem functioning in headwater streams that have been modified for agricultural drainage. Although further research on whole stream metabolism in these systems would be beneficial, my results suggest that water quality and ecosystem function would be improved through greater nutrient uptake capacity and suspended sediment reduction if bench formation were permitted to occur in agricultural drainage ditches.

TABLES

Table 1. Summary of environmental parameters for all nine study sites in the River Raisin Watershed, Michigan.

	Width (m)	Depth (m)	Cross Section (m^2)	Velocity (m min^{-1})	Q (L s^{-1})	% of incident PAR reaching stream surface	% of bottom covered by submerged vegetation	Chlorophyll *a* (µg L^{-1})	TP (µg L^{-1})	NH_4 (µg L^{-1})	NO_3 (mg L^{-1})	TSS (mg L^{-1})	SOM (mg L^{-1})	% OM in sediment
Benched														
Minimum	0.7	0.1	0.13	0.11	0.1	2.1	42.0	0.98	26.9	4.9	0.15	2.5	1.5	1.8
Maximum	3.1	0.3	0.77	18.82	151.5	94.6	100.0	59.90	179.8	212.2	9.51	23.8	11.4	7.9
Mean	1.8	0.2	0.37	4.35	29.3	39.1	76.5	8.85	74.8	41.0	2.74	6.5	3.1	4.4
Trapezoidal														
Minimum	1.3	0.1	0.08	0.29	0.0	8.5	5.4	0.73	10.2	8.5	0.49	4.6	2.1	1.8
Maximum	5.6	0.5	2.80	15.17	704.9	89.2	74.8	9.00	462.6	173.0	11.83	342.0	35.4	3.0
Mean	2.6	0.2	0.61	6.31	98.1	40.5	34.3	3.15	75.4	55.8	3.64	33.8	5.3	2.4
Reference														
Minimum	3.4	0.2	0.79	1.30	22.8	3.4	0.0	1.20	19.5	16.0	0.14	7.5	2.6	1.3
Maximum	5.3	0.5	1.98	18.99	620.3	63.3	23.5	11.51	217.9	259.3	2.19	74.0	11.3	2.7
Mean	4.1	0.3	1.25	7.64	168.2	30.1	7.8	5.10	83.7	84.8	0.53	28.8	5.7	2.0

Q = stream discharge, PAR = photosynthetically active radiation, TP = total phosphorus, NH_4 = ammonia, NO_3 = nitrate, TSS = total suspended solids, SOM = suspended organic matter, OM = organic matter

Table 2. Values of K' (the oxygen diffusion coefficient) for a range of stream discharge (APHA 1998).

Discharge (m^3 s^{-1})	**K' (s m^{-1} day^{-1})**
0.028-0.28	28.3 x 10^3
0.28-0.56	21.3 x 10^3
>0.56	15.3 x 10^3

Table 3. Summary of ANOVA statistical results for the three metabolism sites in the River Raisin Watershed, Michigan.

Parameter (mean)	**site**	**>, <, or =**	**site**	***p***
% of incident PAR reaching stream surface	R	<	T	<0.005
	R	<	B	0.001
	T	=	B	ns
% of bottom covered by submerged vegetation	R	=	T	ns
	R	<	B	<0.005
	T	<	B	<0.005
TP (ug L^{-1})	R	=	T	ns
	R	=	B	ns
	T	=	B	ns
log NO_3 (mg L^{-1})	R	<	T	<0.005
	R	<	B	0.009
	T	>	B	0.024
NH_4 (ug L^{-1})	R	=	T	ns
	R	=	B	ns
	T	=	B	ns
Chlorophyll *a* (ug L^{-1})	R	=	T	ns
	R	=	B	ns
	T	=	B	ns
TSS (mg L^{-1})	R	=	T	ns
	R	>	B	0.033
	T	=	B	ns
OSM (mg L^{-1})	R	=	T	ns
	R	=	B	ns
	T	=	B	ns
log Q (L sec^{-1})	R	=	T	ns
	R	>	B	<0.005
	T	>	B	0.004
Velocity (m min^{-1})	R	=	T	ns
	R	>	B	0.003
	T	=	B	ns
k_{O2} (min^{-1})	R	>	T	<0.005
	R	>	B	<0.005
	T	>	B	<0.005

R = reference site, T = trapezoidal site, B = benched site, ns = not significant, PAR = photosynthetically active radiation, TP = total phosphorus, NO_3 = nitrate, NH_4 = ammonia, TSS = total suspended solids, OSM = organic suspended matter, Q = stream discharge, k_{O2} = temperature corrected oxygen reaeration coefficient.

Table 4. Summary of environmental parameters for the three metabolism sites in the River Raisin Watershed, Michigan.

	Date	Width (m)	Depth (m)	Cross Section (m^2)	Velocity (m min^{-1})	Q (L s^{-1})	% of incident PAR reaching stream surface	% of bottom covered by submerged vegetation	Chlorophyll *a* (µg L^{-1})	TP (µg L^{-1})	NH_4 (µg L^{-1})	NO_3 (mg L^{-1})	TSS (mg L^{-1})	SOM (mg L^{-1})	% OM in sediment
Benched															
B6	13-May-08	1.8	0.3	0.48	6.35	50.0	94.6	60.3	59.90	49.0	15.3	0.71	23.8	9.3	1.8
	6-Jun-08	2.0	0.3	0.56	2.06	14.8	76.9	91.6	9.53	44.9	56.0	0.48	4.3	2.4	
	11-Jun-08	2.4	0.3	0.61	4.21	42.7	67.4		3.21	57.1	54.4	2.83	4.4	2.6	
	17-Jun-08	1.8	0.2	0.46	1.82	12.8	52.8	100.0	4.49	28.7	15.5	0.60	4.2	3.1	
	24-Jun-08	1.9	0.2	0.39	2.81	16.6	60.9	96.7	2.13	28.4	14.4	0.30	3.0	2.1	
	2-Jul-08	1.9	0.2	0.38	2.36	14.0	55.4	98.6	5.00	42.2	18.9	0.42	5.6	2.2	
Mean		**2.0**	**0.2**	**0.48**	**3.27**	**25.2**	**68.0**	**89.4**	**14.04**	**41.7**	**29.1**	**0.89**	**7.5**	**3.6**	
Trapezoidal															
T32	13-May-08	2.3	0.3	0.73	10.09	123.2	89.2	8.0	4.83	10.2	23.6	1.73	8.1	2.3	1.8
	6-Jun-08	2.5	0.3	0.62	5.71	59.2	76.8	12.5	2.00	34.8	62.3	0.94	15.5	3.6	
	11-Jun-08	2.4	0.4	0.90	14.84	222.4	85.4		2.09	68.6	102.5	7.51	31.0	7.4	
	16-Jun-08	2.3	0.3	0.64	7.01	74.6	87.7	21.0	1.08	29.0	25.4	2.97	9.4	2.3	
	27-Jun-08	2.4	0.3	0.72	6.91	82.2	71.0	5.4	0.73	22.9	22.3	1.37	9.0	2.7	
Mean		**2.4**	**0.3**	**0.72**	**8.91**	**112.3**	**82.0**	**11.7**	**2.15**	**33.1**	**47.2**	**2.91**	**14.6**	**3.6**	
Reference															
R37	15-May-08	4.4	0.5	1.98	18.99	620.3	39.4		5.51	25.4	16.0	0.14	37.0	7.3	1.9
	9-Jun-08	4.3	0.3	1.12	11.30	209.5	43.3	0.0	3.09	28.6	42.9	0.16	34.8	7.5	
	11-Jun-08	4.6	0.4	1.62	17.66	475.2	18.5		3.68	57.4	36.7	0.15	50.4	9.8	
	17-Jun-08	4.4	0.2	0.99	7.83	127.4	3.4	0.0	1.20	24.1	25.7	0.16	13.2	3.3	
	27-Jun-08	4.3	0.2	0.95	8.21	126.9	13.5	0.0	1.38	19.5	18.4	0.16	8.0	2.6	
Mean		**4.4**	**0.3**	**1.33**	**12.80**	**311.9**	**23.6**	**0.0**	**2.97**	**31.0**	**27.9**	**0.15**	**28.7**	**6.1**	

Q = stream discharge, PAR = photosynthetically active radiation, TP = total phosphorus, NH_4 = ammonia, NO_3 = nitrate, TSS = total suspended solids, SOM = suspended organic matter, OM = organic matter

Table 5. Summary of daily rates of GPP, ER, NDM, P:R, and k_{O2} for the three metabolism sites in the River Raisin Watershed, Michigan.

	ER ($g\ O_2\ m^{-2}\ day^{-1}$)			**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**			**NDM ($g\ O_2\ m^{-2}\ day^{-1}$)**			**P:R**			**Mean k_{O2} (min^{-1})**		
	Minimum	Maximum	**Mean**	Minimum	Maximum	**Mean**	Minimum	Maximum	**Mean**	Minimum	Maximum	**Mean**	Minimum	Maximum	**Mean**
Reference	-1.54	-10.46	**-5.44**	0.05	2.62	**0.92**	-9.14	-1.47	**-4.52**	0.00	0.30	**0.16**	0.0084	0.0149	**0.0115**
Trapezoidal	-2.01	-12.70	**-4.99**	1.00	5.05	**2.02**	-9.52	0.29	**-2.97**	0.15	1.13	**0.48**	0.0056	0.0146	**0.0081**
Benched	-6.69	-21.87	**-11.05**	7.06	22.36	**12.11**	-4.19	4.08	**1.06**	0.63	1.34	**1.10**	0.0021	0.0072	**0.0034**

Table 6. Summary of significant ($\alpha = 0.05$) and marginally significant correlations between rates of metabolism and environmental parameters for the three metabolism sites in the River Raisin Watershed, Michigan. Table shows Pearson correlation coefficients (*r*).

	Reference Site		**Trapezoidal Site**		**Benched Site**	
	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**	**ER ($g\ O_2\ m^{-2}\ day^{-1}$)**	**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**	**ER ($g\ O_2\ m^{-2}\ day^{-1}$)**	**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**
ER ($g\ O_2\ m^{-2}\ day^{-1}$)	-	-	-	-	-	-
GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	-	-	-	-	0.940	-
% of incident PAR reaching stream surface	0.877	-	-	-	-	-
% of bottom covered by submerged vegetation	-	-	-0.858	-	-	-
Chlorophyll *a* ($ug\ L^{-1}$)	0.900	0.851	-	-	-	-
TP ($ug\ L^{-1}$)	-	-	0.698	0.966	0.774	0.614
NH_4 ($ug\ L^{-1}$)	-	-	0.776	0.816	0.872	0.928
NO_3 ($mg\ L^{-1}$)	-	-0.992	0.804	0.878	0.875	0.814
TSS ($mg\ L^{-1}$)	-	-	-	-	-	-
SOM ($mg\ L^{-1}$)	0.794	-	0.877	0.864	-	-

ER = ecosystem respiration, GPP = gross primary productivity, PAR = photosynthetically active radiation, TP = total phosphorus, NH_4 = ammonia, NO_3 = nitrate, TSS = total suspended solids, SOM = suspended organic matter.

Table 7. Daily rates of ER, GPP, NDM, P:R, and k_{O2} for the reference metabolism site in the River Raisin Watershed, Michigan.

Date	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	NDM ($g\ O_2\ m^{-2}\ day^{-1}$)	P:R	Mean k_{O2} (min^{-1})
16-May-08	-10.46	2.62	-7.84	0.25	0.0127
17-May-08	-9.36	2.11	-7.25	0.23	0.0121
18-May-08	-8.12	1.68	-6.44	0.21	0.0106
19-May-08	-6.98	2.10	-4.88	0.30	0.0096
20-May-08	-7.16	1.93	-5.24	0.27	0.0108
21-May-08	-7.58	2.30	-5.28	0.30	0.0115
10-Jun-08	-9.18	0.05	-9.14	0.00	0.0149
11-Jun-08	-8.81	0.89	-7.92	0.10	0.0147
12-Jun-08	-5.64	0.93	-4.71	0.17	0.0124
13-Jun-08	-5.68	0.55	-5.13	0.10	0.0144
14-Jun-08	-5.28	0.77	-4.51	0.15	0.0137
15-Jun-08	-4.54	0.62	-3.92	0.14	0.0119
16-Jun-08	-4.03	0.51	-3.52	0.13	0.0108
17-Jun-08	-3.20	0.29	-2.91	0.09	0.0092
18-Jun-08	-2.98	0.44	-2.54	0.15	0.0086
19-Jun-08	-2.31	0.19	-2.12	0.08	0.0084
20-Jun-08	-1.54	0.07	-1.47	0.05	0.0085
21-Jun-08	-2.42	0.21	-2.21	0.09	0.0088
22-Jun-08	-2.90	0.66	-2.24	0.23	0.0094
28-Jun-08	-5.97	0.24	-5.72	0.04	0.0134
29-Jun-08	-4.80	0.44	-4.36	0.09	0.0131
30-Jun-08	-3.00	0.64	-2.37	0.21	0.0118
1-Jul-08	-3.20	0.92	-2.28	0.29	0.0132
Mean	**-5.44**	**0.92**	**-4.52**	**0.16**	**0.0115**
Minimum	**-1.54**	**0.05**	**-9.14**	**0.00**	**0.0084**
Maximum	**-10.46**	**2.62**	**-1.47**	**0.30**	**0.0149**

Table 8. Daily rates of ER, GPP, NDM, P:R, and k_{O2} for the trapezoidal metabolism site in the River Raisin Watershed, Michigan.

Date	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	NDM ($g\ O_2\ m^{-2}\ day^{-1}$)	P:R	Mean k_{O2} (min^{-1})
14-May-08	-7.15	1.10	-6.05	0.15	0.0091
15-May-08	-6.34	2.68	-3.66	0.42	0.0087
16-May-08	-5.59	2.12	-3.47	0.38	0.0082
17-May-08	-5.49	1.59	-3.90	0.29	0.0081
18-May-08	-6.84	1.00	-5.83	0.15	0.0097
19-May-08	-5.64	1.69	-3.96	0.30	0.0082
20-May-08	-4.88	1.42	-3.46	0.29	0.0073
21-May-08	-4.24	1.20	-3.04	0.28	0.0069
7-Jun-08	-4.87	1.86	-3.01	0.38	0.0068
8-Jun-08	-4.69	1.97	-2.73	0.42	0.0071
9-Jun-08	-10.17	5.05	-5.12	0.50	0.0085
11-Jun-08	-12.70	3.18	-9.52	0.25	0.0146
12-Jun-08	-5.03	2.11	-2.92	0.42	0.0094
13-Jun-08	-4.56	1.35	-3.22	0.30	0.0089
14-Jun-08	-5.00	2.72	-2.27	0.54	0.0100
15-Jun-08	-4.19	2.54	-1.65	0.61	0.0077
16-Jun-08	-2.83	2.17	-0.66	0.77	0.0071
17-Jun-08	-2.35	1.91	-0.44	0.81	0.0063
18-Jun-08	-2.01	1.63	-0.38	0.81	0.0057
19-Jun-08	-2.06	2.04	-0.02	0.99	0.0057
20-Jun-08	-2.32	2.61	0.29	1.13	0.0056
28-Jun-08	-5.51	1.74	-3.77	0.32	0.0107
29-Jun-08	-4.04	1.36	-2.68	0.34	0.0085
30-Jun-08	-3.34	1.66	-1.68	0.50	0.0074
1-Jul-08	-2.82	1.72	-1.11	0.61	0.0065
Mean	**-4.99**	**2.02**	**-2.97**	**0.48**	**0.0081**
Minimum	**-2.01**	**1.00**	**-9.52**	**0.15**	**0.0056**
Maximum	**-12.70**	**5.05**	**0.29**	**1.13**	**0.0146**

Table 9. Daily rates of ER, GPP, NDM, P:R, and k_{O2} for the benched metabolism site in the River Raisin Watershed, Michigan.

Date	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	NDM ($g\ O_2\ m^{-2}\ day^{-1}$)	P:R	Mean k_{O2} (min^{-1})
14-May-08	-11.25	7.06	-4.19	0.63	0.0035
15-May-08	-10.42	12.37	1.95	1.19	0.0035
16-May-08	-10.17	12.66	2.49	1.24	0.0035
17-May-08	-9.48	9.95	0.47	1.05	0.0033
18-May-08	-10.68	10.72	0.04	1.00	0.0032
19-May-08	-9.45	10.65	1.19	1.13	0.0030
20-May-08	-8.07	8.42	0.35	1.04	0.0029
21-May-08	-8.50	9.75	1.25	1.15	0.0028
7-Jun-08	-15.20	16.48	1.28	1.08	0.0034
8-Jun-08	-11.98	16.07	4.08	1.34	0.0039
9-Jun-08	-13.64	16.83	3.20	1.23	0.0037
10-Jun-08	-21.42	22.29	0.87	1.04	0.0072
11-Jun-08	-21.87	22.36	0.49	1.02	0.0062
12-Jun-08	-15.61	18.52	2.91	1.19	0.0043
13-Jun-08	-11.05	8.93	-2.12	0.81	0.0039
14-Jun-08	-13.98	17.54	3.56	1.25	0.0042
15-Jun-08	-10.61	13.89	3.28	1.31	0.0034
16-Jun-08	-10.03	11.91	1.88	1.19	0.0030
17-Jun-08	-9.10	10.03	0.93	1.10	0.0026
18-Jun-08	-9.96	10.57	0.61	1.06	0.0023
19-Jun-08	-8.44	9.57	1.13	1.13	0.0023
20-Jun-08	-8.79	10.47	1.67	1.19	0.0023
21-Jun-08	-6.69	7.78	1.09	1.16	0.0024
22-Jun-08	-7.85	8.99	1.14	1.14	0.0025
25-Jun-08	-8.03	8.22	0.19	1.02	0.0021
26-Jun-08	-7.16	9.04	1.88	1.26	0.0025
30-Jun-08	-12.76	9.74	-3.02	0.76	0.0046
1-Jul-08	-7.26	8.29	1.03	1.14	0.0030
Mean	**-11.05**	**12.11**	**1.06**	**1.10**	**0.0034**
Minimum	**-6.69**	**7.06**	**-4.19**	**0.63**	**0.0021**
Maximum	**-21.87**	**22.36**	**4.08**	**1.34**	**0.0072**

FIGURES

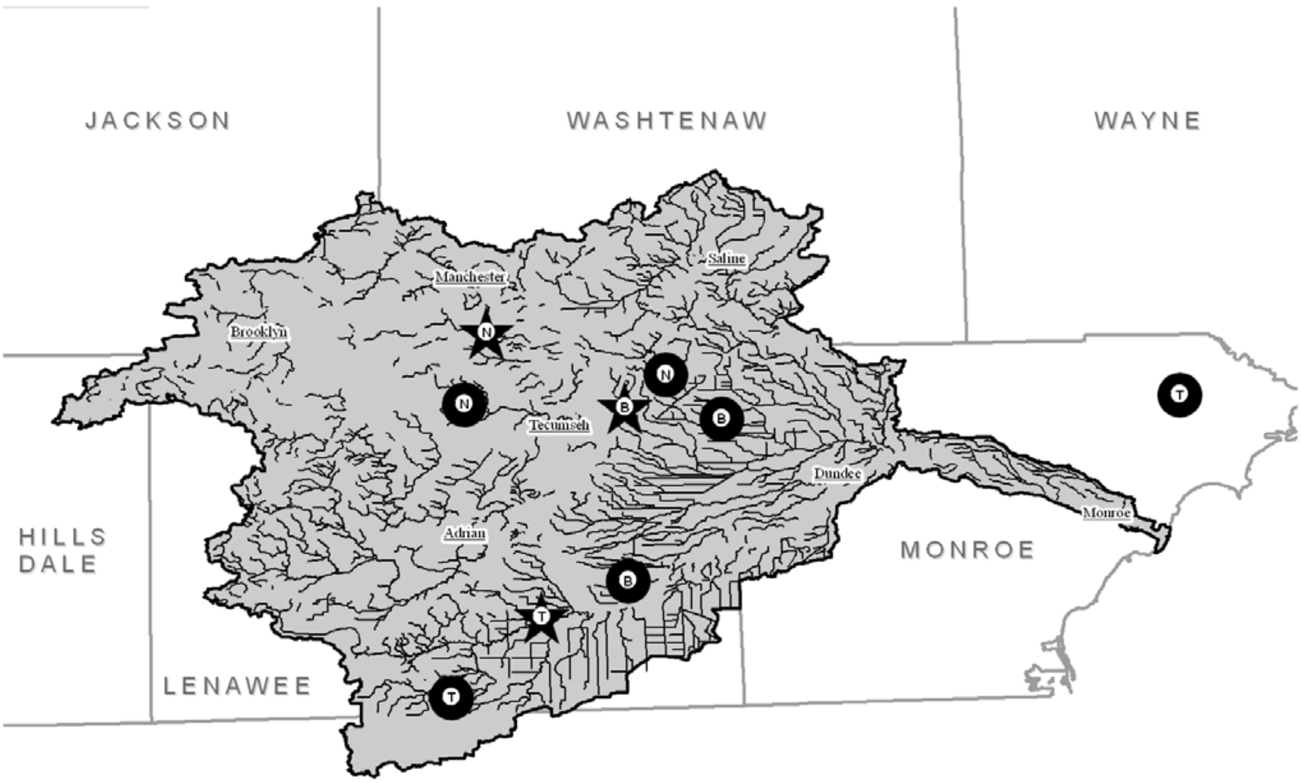

Figure 1. Location of study sites in the River Raisin Watershed, Michigan. N = Natural "Reference" sites, T = Trapezoidal sites, B = Benched sites. Stars represent sites that were selected for metabolism measurements. GPS locations courtesy of Janssen 2008.

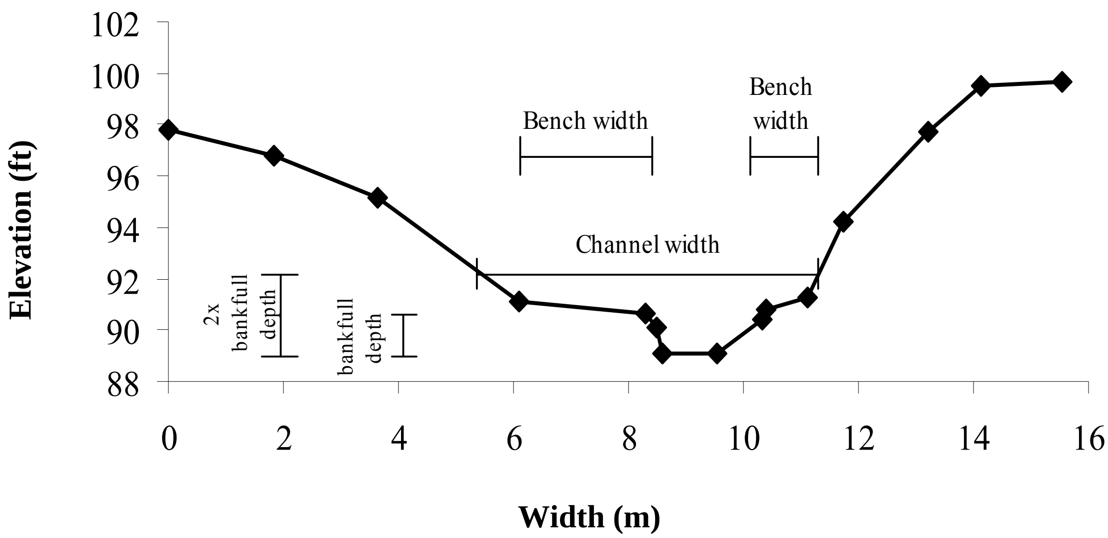

Figure 2. Cross-section depicting channel morphology measurements at the benched metabolism site (data courtesy of Janssen 2008).

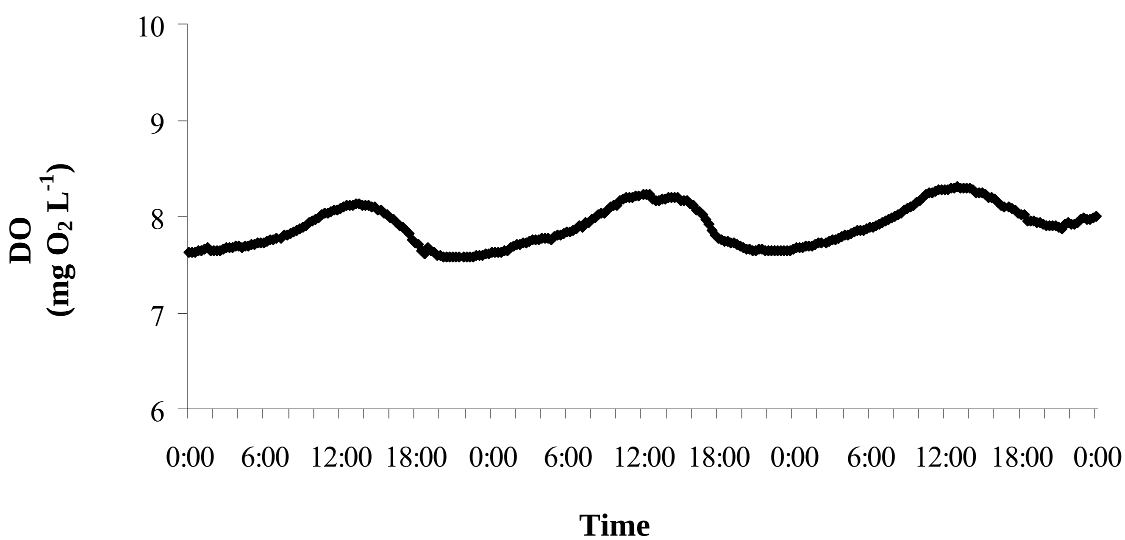

Figure 3. Diel variation in dissolved oxygen for the reference site, 14-16 June 2008.

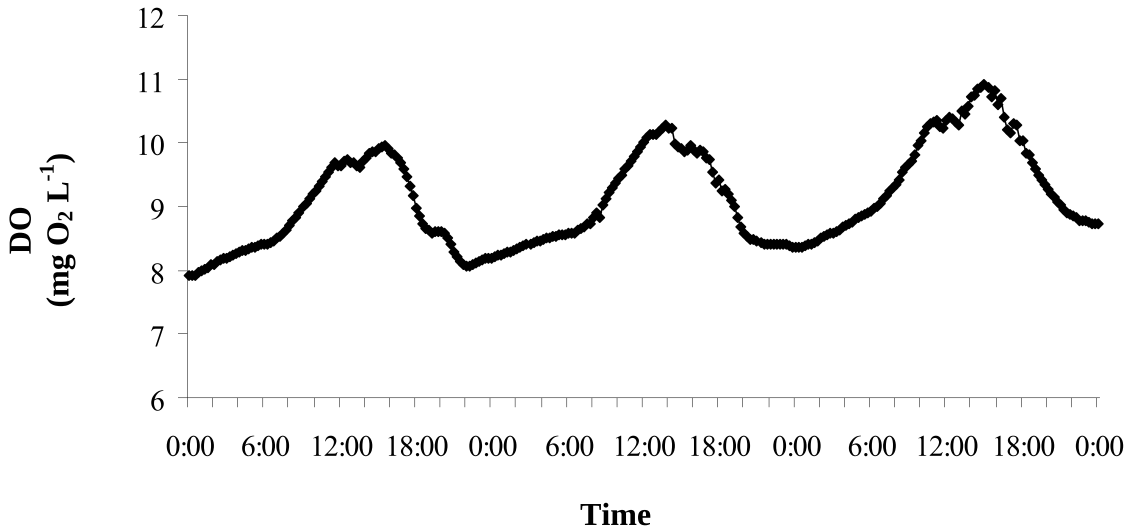

Figure 4. Diel variation in dissolved oxygen for the trapezoidal site, 15-17 June 2008.

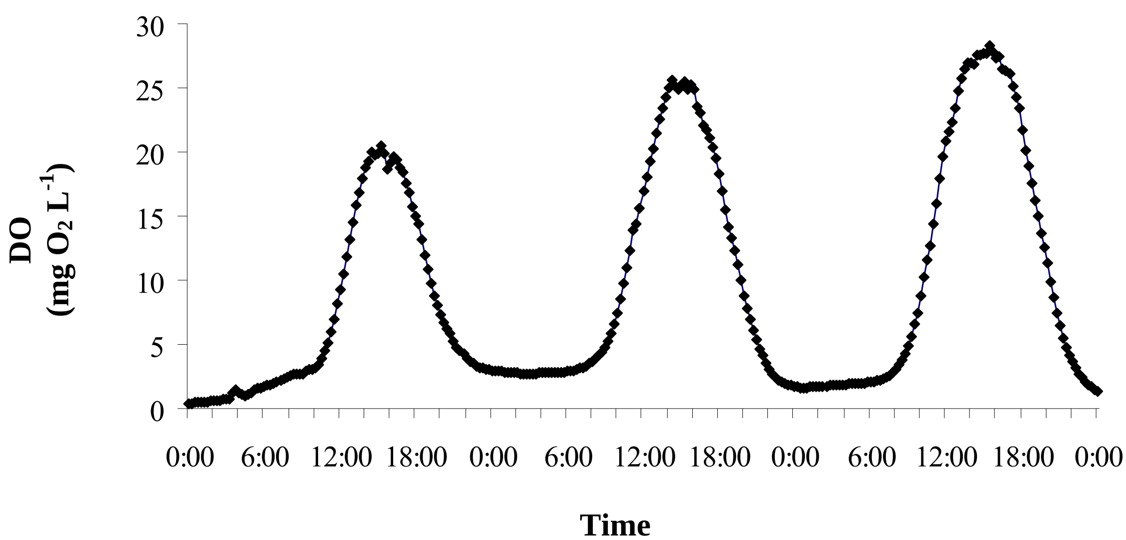

Figure 5. Diel variation in dissolved oxygen for the benched site, 10-12 June 2008.

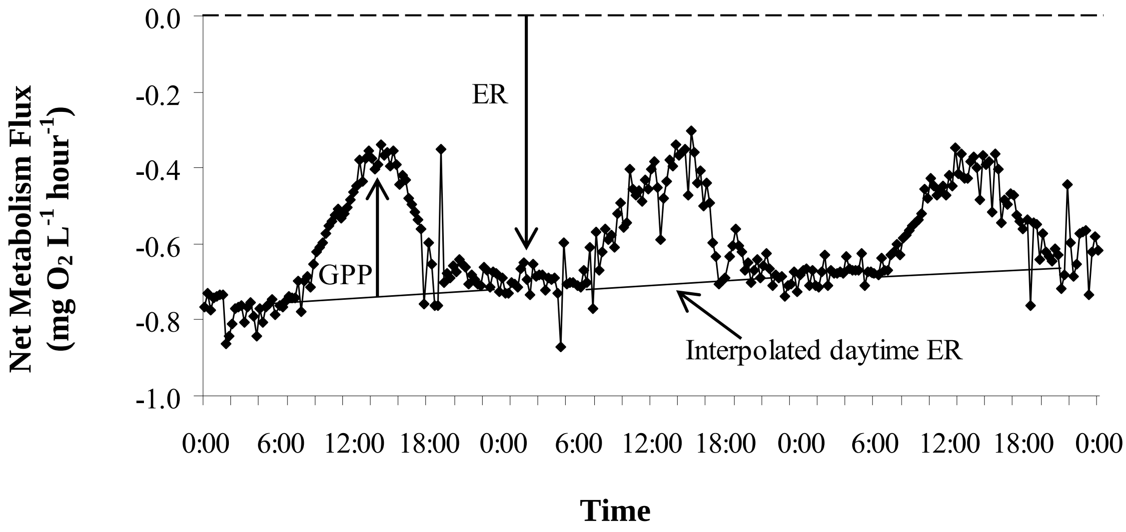

Figure 6. Rates of net daily metabolism for the reference site, 14-16 June 2008. Arrows show the area representing gross primary productivity (GPP) and ecosystem respiration (ER). The solid line indicates the interpolated daytime ER. The dashed line represents a net metabolism flux of zero.

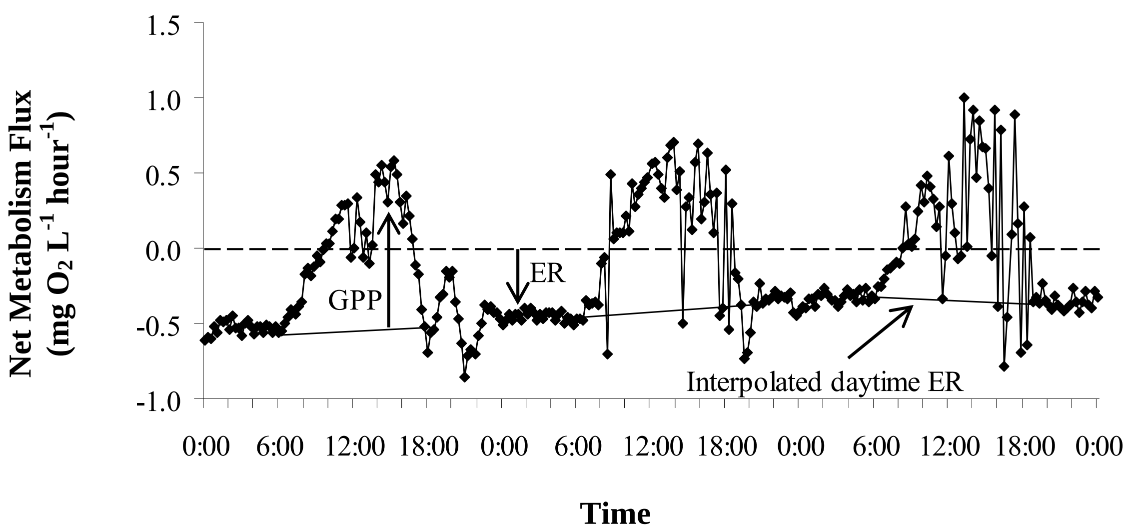

Figure 7. Rates of net daily metabolism for the trapezoidal site, 15-17 June 2008. Arrows show the area representing gross primary productivity (GPP) and ecosystem respiration (ER). The solid line indicates the interpolated daytime ER. The dashed line represents a net metabolism flux of zero.

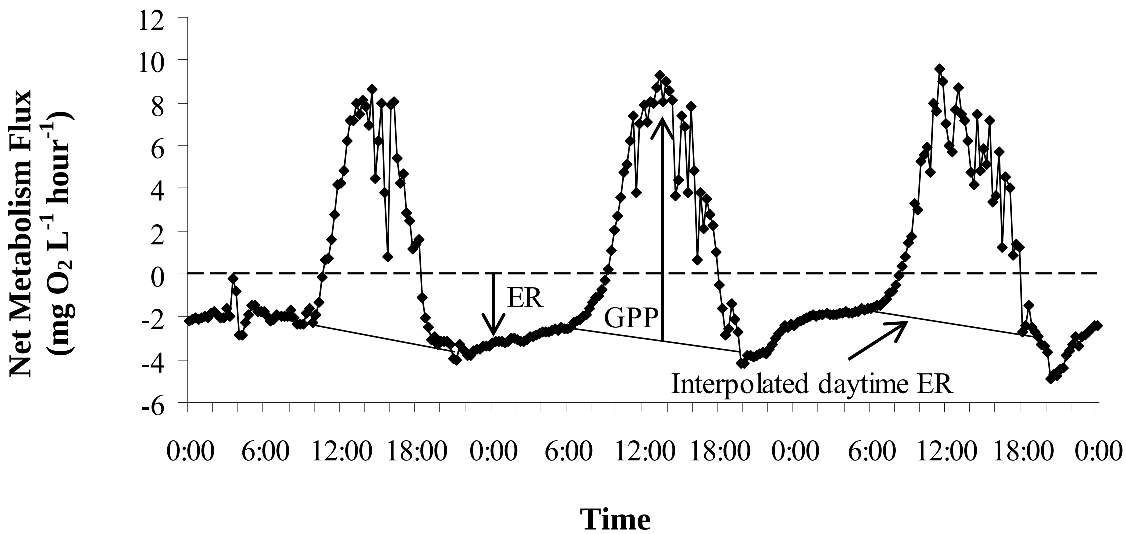

Figure 8. Rates of net daily metabolism for the benched site, 10-12 June 2008. Arrows show the area representing gross primary productivity (GPP) and ecosystem respiration (ER). The solid line indicates the interpolated daytime ER. The dashed line represents a net metabolism flux of zero.

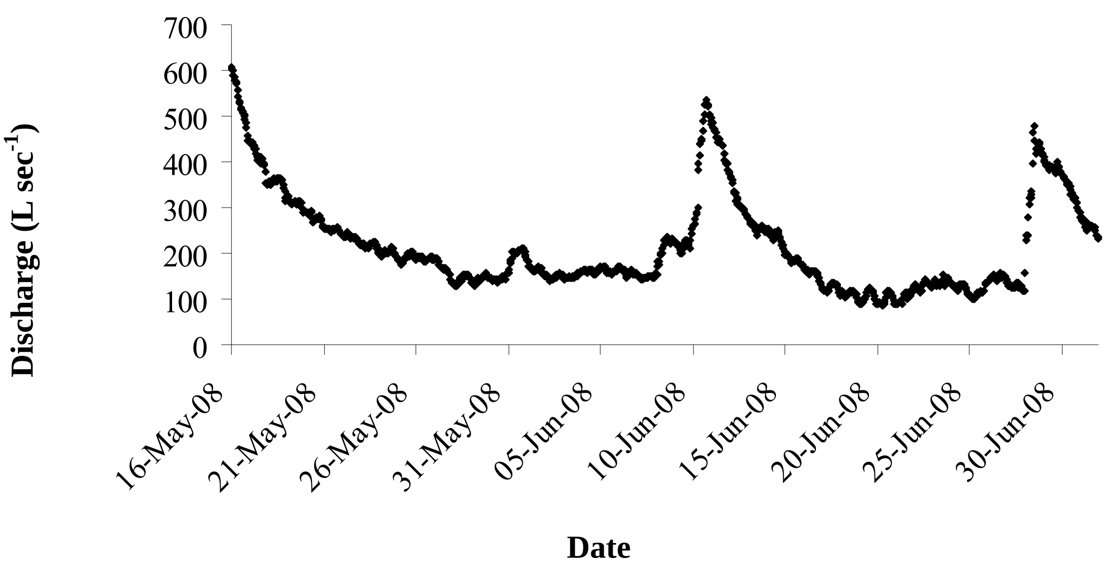

Figure 9. Hydrograph for the reference site, 16 May – 1 July 2008.

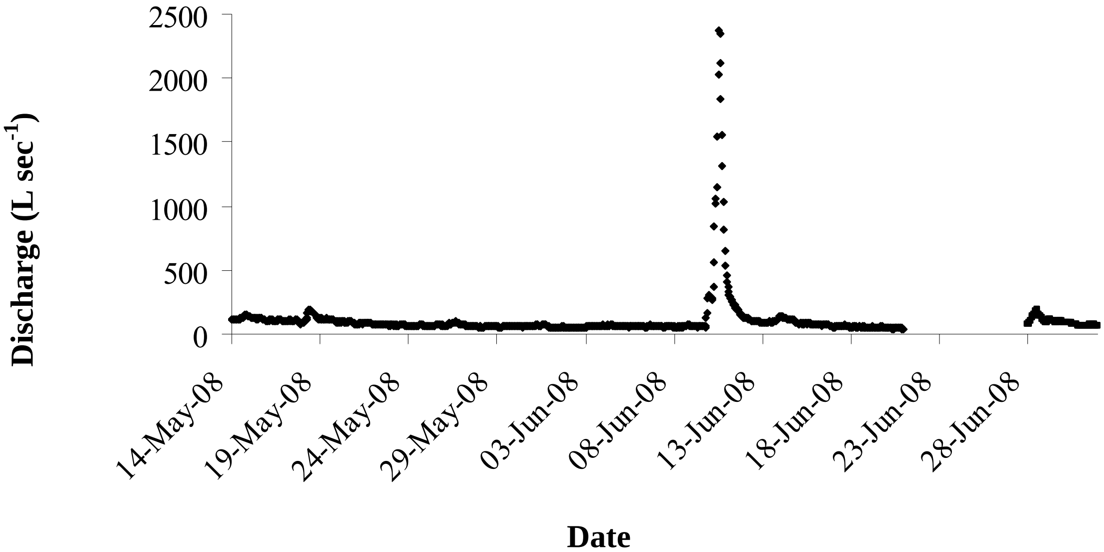

Figure 10. Hydrograph for the trapezoidal site, 14 May – 20 June 2008 and 28 June – 1 July 2008.

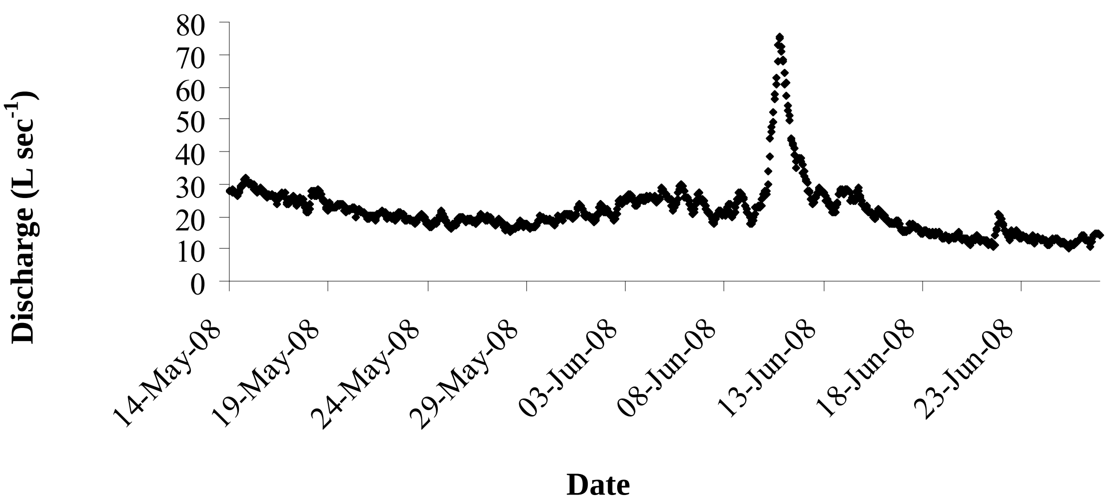

Figure 11. Hydrograph for the benched site, 14 May – 26 June 2008.

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APPENDIX

Figure A. Scatterplots of correlations for GPP and ER at the reference site. Only significant correlations are graphed here. See Table D in appendix for full correlation matrix.

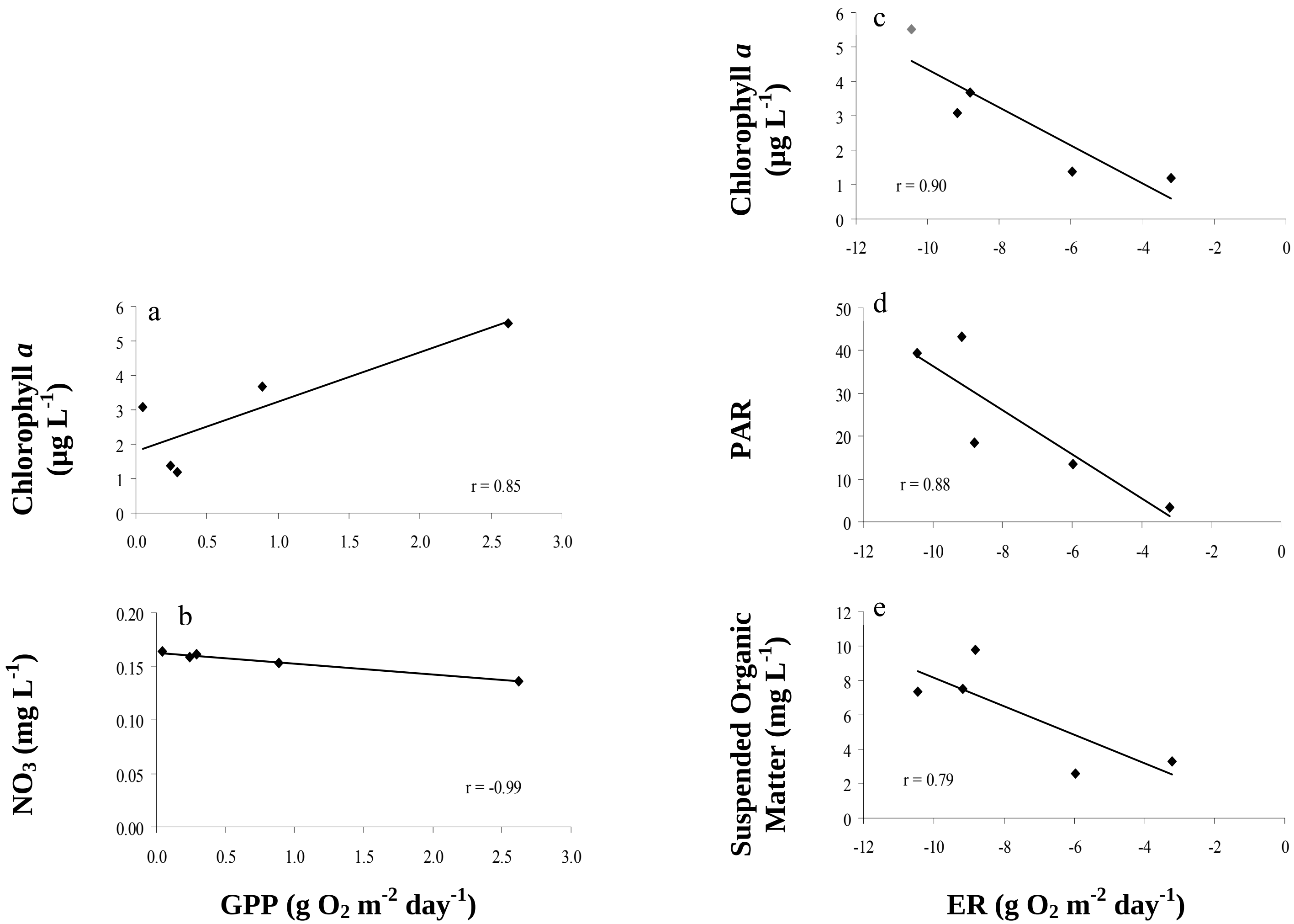

Figure B. Scatterplots of correlations for GPP at the trapezoidal site. Only significant correlations are graphed here. See Table E in appendix for full correlation matrix.

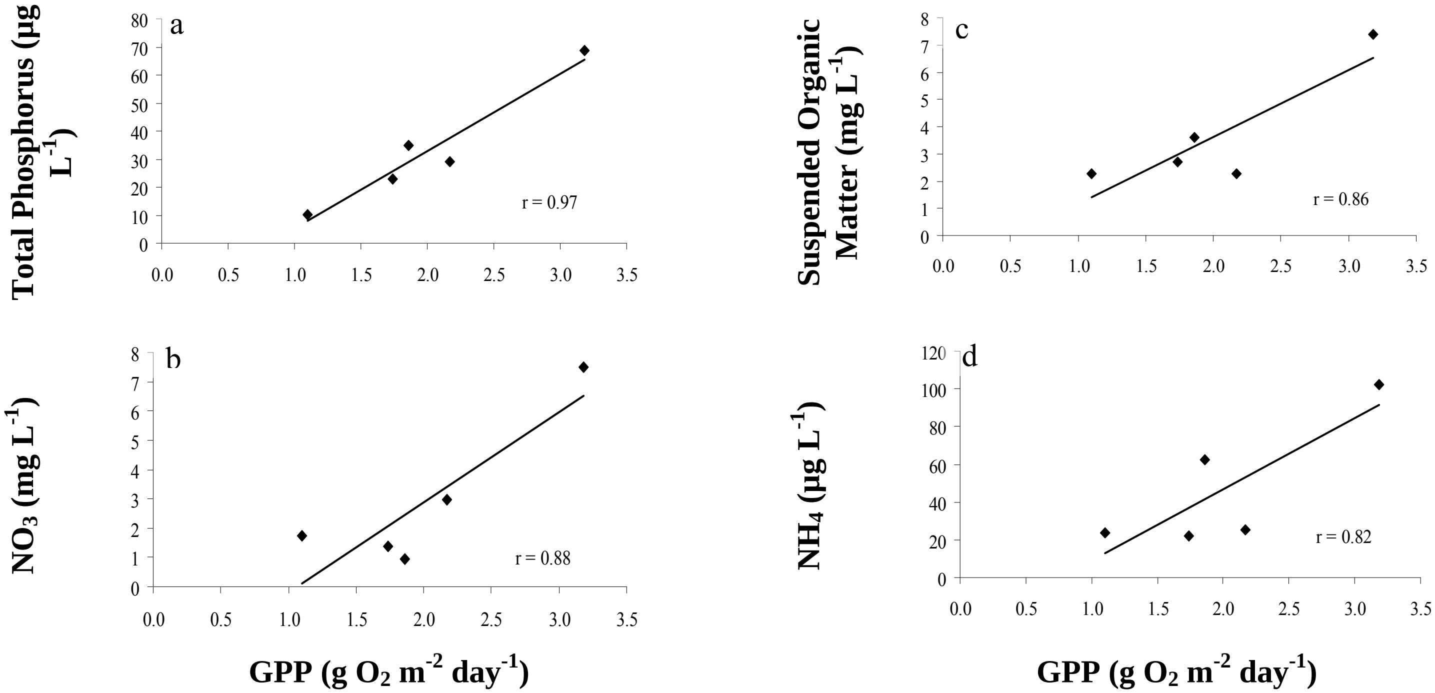

Figure B. continued. Scatterplots of correlations for ER at the trapezoidal site. Only significant correlations are graphed here. See Table E in appendix for full correlation matrix.

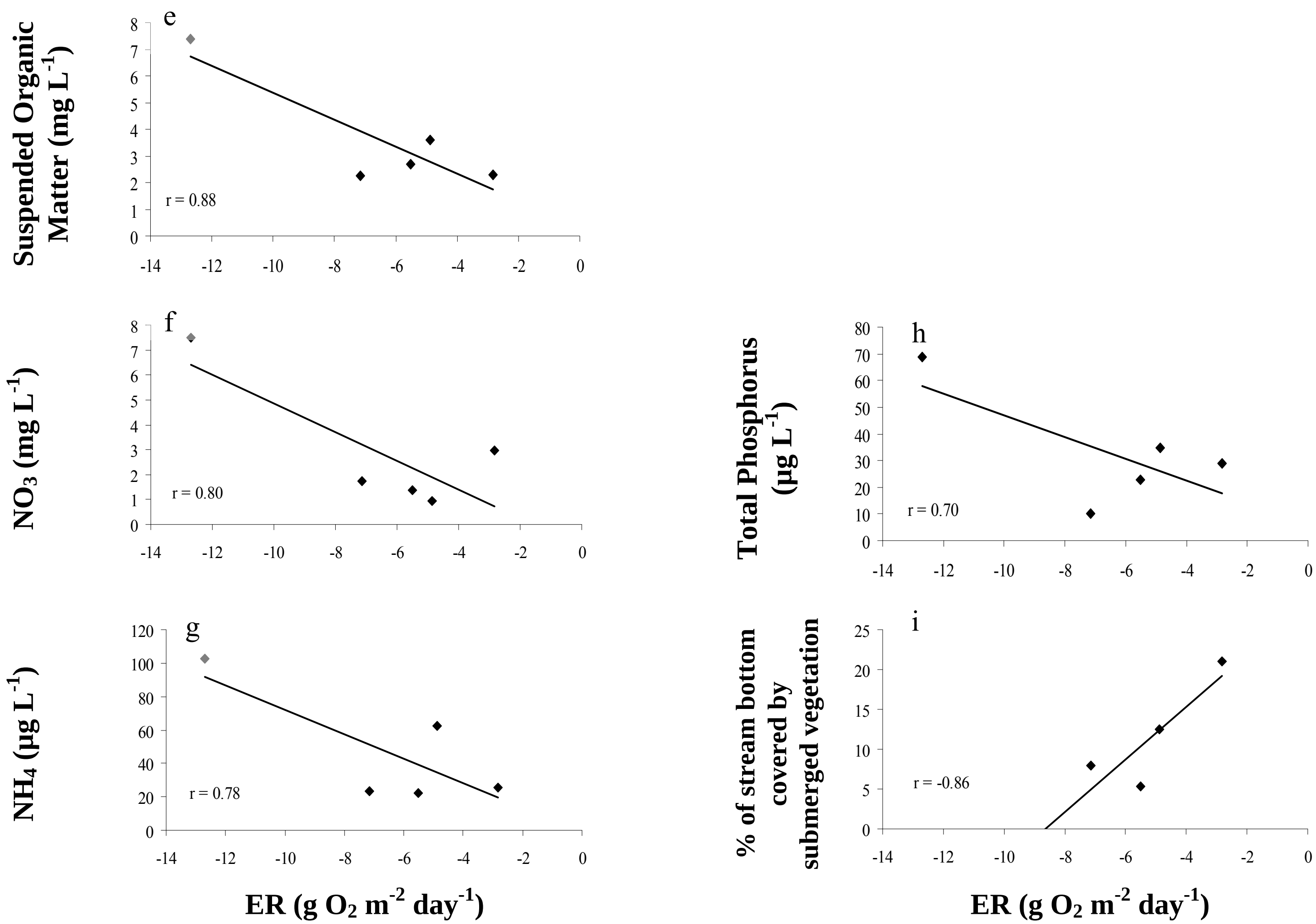

Figure C. Scatterplots of correlations for GPP and ER at the benched site. Only significant correlations are graphed here. See Table F in appendix for full correlation matrix.

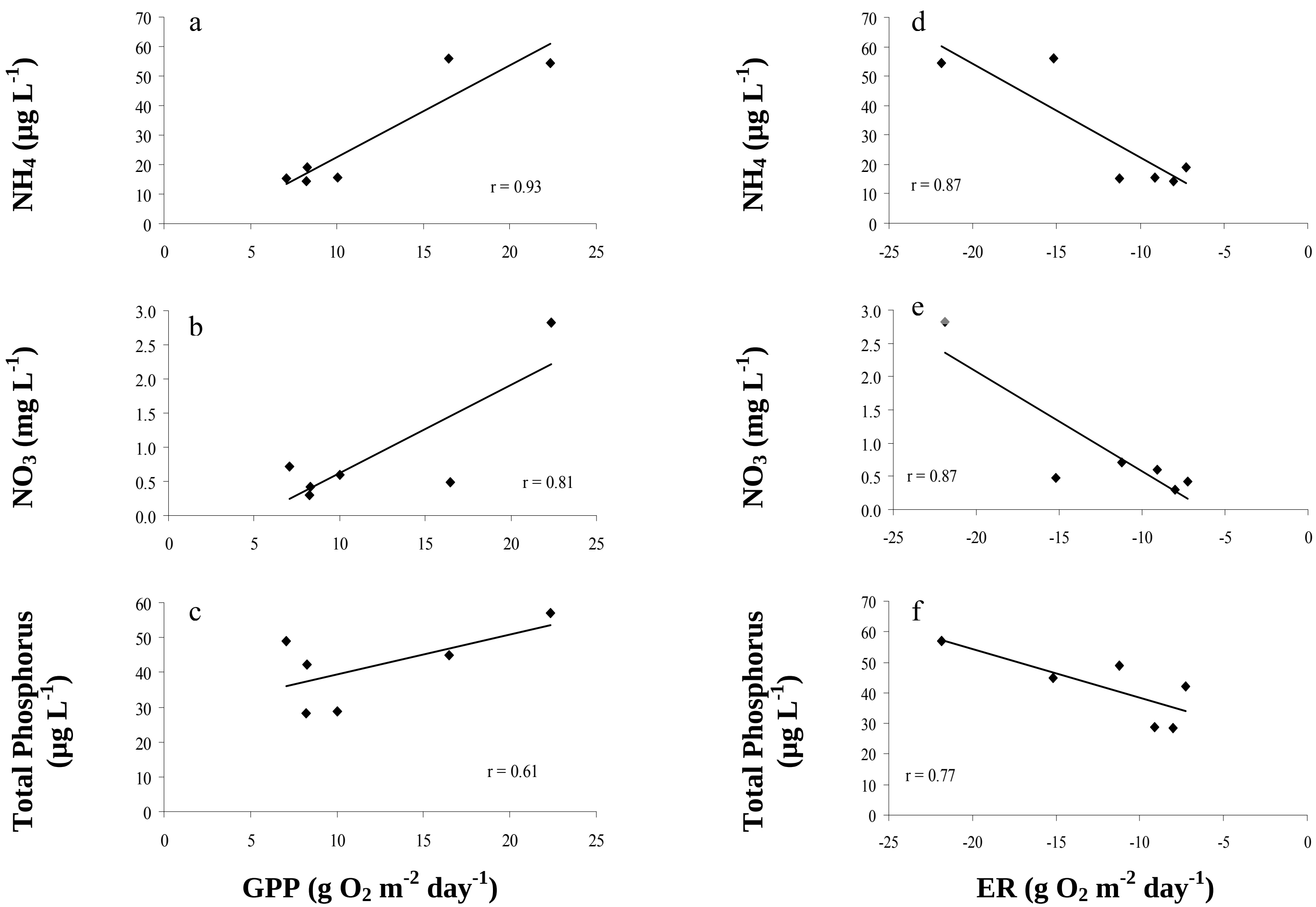

Figure D. Scatterplots of correlations between GPP and ER for each metabolism site. Only the correlation at the benched site was significant.

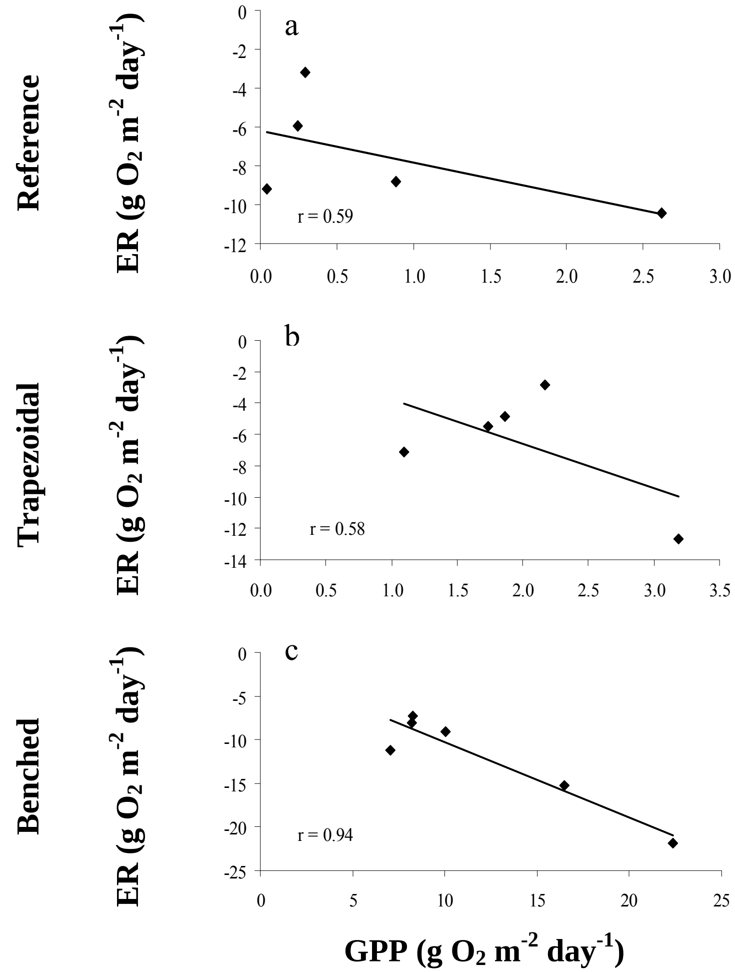

Table A. Summary of weekly data for environmental parameters at the benched site in the River Raisin Watershed, Michigan.

	Date	Width (m)	Depth (m)	Cross Section (m^2)	Velocity (m min^{-1})	Q (L s^{-1})	% of incident PAR reaching stream surface	% of bottom covered by submerged vegetation	Chlorophyll *a* (µg L^{-1})	TP (µg L^{-1})	NH_4 (µg L^{-1})	NO_3 (mg L^{-1})	TSS (mg L^{-1})	SOM (mg L^{-1})	% OM in sediment
BENCHED															
B6	13-May-08	1.8	0.3	0.48	6.35	50.0	94.6	60.3	59.90	49.0	15.3	0.71	23.8	9.3	1.8
	6-Jun-08	2.0	0.3	0.56	2.06	14.8	76.9	91.6	9.53	44.9	56.0	0.48	4.3	2.4	
	11-Jun-08	2.4	0.3	0.61	4.21	42.7	67.4		3.21	57.1	54.4	2.83	4.4	2.6	
	17-Jun-08	1.8	0.2	0.46	1.82	12.8	52.8	100.0	4.49	28.7	15.5	0.60	4.2	3.1	
	24-Jun-08	1.9	0.2	0.39	2.81	16.6	60.9	96.7	2.13	28.4	14.4	0.30	3.0	2.1	
	2-Jul-08	1.9	0.2	0.38	2.36	14.0	55.4	98.6	5.00	42.2	18.9	0.42	5.6	2.2	
Minimum		**1.8**	**0.2**	**0.4**	**1.8**	**12.8**	**52.8**	**60.3**	**2.13**	**28.4**	**14.4**	**0.30**	**3.0**	**2.1**	
Maximum		**2.4**	**0.3**	**0.6**	**6.3**	**50.0**	**94.6**	**100.0**	**59.90**	**57.1**	**56.0**	**2.83**	**23.8**	**9.3**	
Mean		**2.0**	**0.2**	**0.5**	**3.3**	**25.2**	**68.0**	**89.4**	**14.04**	**41.7**	**29.1**	**0.89**	**7.5**	**3.6**	
BENCHED															
B18	16-May-08	2.3	0.2	0.30	18.8	79.7	44.1	51.0	4.55	113.1	212.2	4.93	5.5	2.0	2.9
	9-Jun-08	2.7	0.1	0.30	5.5	27.4		71.9	3.00	179.8	56.5	2.19	3.4	1.5	
	16-Jun-08	3.1	0.3	0.77	13.2	151.5	4.0	42.0	1.77	88.4	48.1	9.51	6.4	2.7	
	24-Jun-08	2.6	0.2	0.67	7.7	54.6	3.0	50.9	1.24	64.3	16.4	4.76	3.6	2.1	2.8
	2-Jul-08	2.4	0.1	0.33	4.7	19.3	2.1	44.3	3.56	126.0	42.5	2.47	5.0	2.0	
Minimum		**2.3**	**0.1**	**0.3**	**4.7**	**19.3**	**2.1**	**42.0**	**1.24**	**64.3**	**16.4**	**2.19**	**3.4**	**1.5**	**2.8**
Maximum		**3.1**	**0.3**	**0.8**	**18.8**	**151.5**	**44.1**	**71.9**	**4.55**	**179.8**	**212.2**	**9.51**	**6.4**	**2.7**	**2.9**
Mean		**2.6**	**0.2**	**0.5**	**10.0**	**66.5**	**13.3**	**52.0**	**2.82**	**114.3**	**75.1**	**4.77**	**4.8**	**2.1**	**2.8**
BENCHED															
B28	15-May-08	1.1	0.2	0.22	0.5	1.8	42.3	83.4	13.38	26.9	4.9	0.64	4.6	2.0	6.7
	5-Jun-08	0.9	0.2	0.20	0.1	0.1	38.3	97.5	4.36	78.0	11.7	0.15	2.5	1.7	
	12-Jun-08	0.9	0.2	0.17	0.9	2.4	26.4		2.15	53.1	58.7	7.64	4.8	1.8	
	18-Jun-08	0.9	0.2	0.13	0.4	0.9	15.3	94.7	0.98	47.9	12.8	2.02	2.8	2.5	7.9
	25-Jun-08	0.7	0.2	0.13	0.3	0.8	15.1	100.0	29.75	167.4	23.2	0.30	16.8	11.4	
	30-Jun-08	1.1	0.2	0.23	2.3	9.0	27.0	65.3	1.52	76.6	35.3	6.58	10.6	2.1	
Minimum		**0.7**	**0.2**	**0.1**	**0.1**	**0.1**	**15.1**	**65.3**	**0.98**	**26.9**	**4.9**	**0.15**	**2.5**	**1.7**	**6.7**
Maximum		**1.1**	**0.2**	**0.2**	**2.3**	**9.0**	**42.3**	**100.0**	**29.75**	**167.4**	**58.7**	**7.64**	**16.8**	**11.4**	**7.9**
Mean		**0.9**	**0.2**	**0.2**	**0.7**	**2.5**	**27.4**	**88.2**	**8.69**	**75.0**	**24.4**	**2.89**	**7.0**	**3.6**	**7.3**
ALL SITES															
Minimum		**0.7**	**0.1**	**0.1**	**0.1**	**0.1**	**2.1**	**42.0**	**0.98**	**26.9**	**4.9**	**0.15**	**2.5**	**1.5**	**1.8**
Maximum		**3.1**	**0.3**	**0.8**	**18.8**	**151.5**	**94.6**	**100.0**	**59.90**	**179.8**	**212.2**	**9.51**	**23.8**	**11.4**	**7.9**
Mean		**1.8**	**0.2**	**0.4**	**4.4**	**29.3**	**39.1**	**76.5**	**8.85**	**74.8**	**41.0**	**2.74**	**6.5**	**3.1**	**4.4**

Table B. Summary of weekly data for environmental parameters at the trapezoidal site in the River Raisin Watershed, Michigan.

	Date	Width (m)	Depth (m)	Cross Section (m^2)	Velocity ($m\ min^{-1}$)	Q ($L\ s^{-1}$)	% of incident PAR reaching stream surface	% of bottom covered by submerged vegetation	Chlorophyll *a* ($\mu g\ L^{-1}$)	TP ($\mu g\ L^{-1}$)	NH_4 ($\mu g\ L^{-1}$)	NO_3 ($mg\ L^{-1}$)	TSS ($mg\ L^{-1}$)	SOM ($mg\ L^{-1}$)	% OM in sediment
TRAPEZOIDAL															
T14	16-May-08	4.1	0.2	0.89	8.6	128.0	8.5	39.4	7.34	23.6	13.9	5.18	8.6	2.5	2.1
	9-Jun-08	3.6	0.1	0.45	6.3	46.3	31.1	42.2	1.13	90.7	173.0	3.29	7.1	2.3	
	16-Jun-08	5.6	0.5	2.80	15.2	704.9	31.4		6.16	462.6	161.3	11.83	342.0	35.4	
	24-Jun-08	3.8	0.2	0.68	5.0	55.1	28.3	32.9	2.06	122.9	49.9	5.83	33.0	6.7	2.1
	2-Jul-08	3.3	0.1	0.43	3.7	26.3	27.5	43.6	1.87	95.6	21.2	2.16	27.8	4.2	
Minimum		**3.3**	**0.1**	**0.4**	**3.7**	**26.3**	**8.5**	**32.9**	**1.13**	**23.6**	**13.9**	**2.16**	**7.1**	**2.3**	**2.1**
Maximum		**5.6**	**0.5**	**2.8**	**15.2**	**704.9**	**31.4**	**43.6**	**7.34**	**462.6**	**173.0**	**11.83**	**342.0**	**35.4**	**2.1**
Mean		**4.1**	**0.2**	**1.0**	**7.7**	**192.1**	**25.4**	**39.5**	**3.71**	**159.1**	**83.9**	**5.66**	**83.7**	**10.2**	**2.1**
TRAPEZOIDAL															
T26	16-May-08	1.5	0.1	0.12	4.9	5.2	18.2	56.0	4.82	29.9	8.5	0.49	7.0	2.4	3.0
	5-Jun-08	1.3	0.1	0.08	0.3	0.0	26.1	74.8	9.00	51.6	55.5	0.64	6.1	3.8	
	12-Jun-08	1.7	0.1	0.15	2.5	5.3	17.5		2.02	35.6	86.8	4.02	7.0	2.2	
	18-Jun-08	1.4	0.1	0.14	1.5	3.0	8.5	50.4	1.30	26.9	21.4	2.97	4.6	2.1	3.0
	25-Jun-08	1.7	0.1	0.16	2.3	5.9	13.9	37.9	2.16	40.7	16.4	3.52	8.4	2.4	
	30-Jun-08	2.1	0.2	0.28	6.3	28.2	27.6	22.2	1.74	61.4	48.4	3.70	16.8	2.8	
Minimum		**1.3**	**0.1**	**0.1**	**0.3**	**0.0**	**8.5**	**22.2**	**1.30**	**26.9**	**8.5**	**0.49**	**4.6**	**2.1**	**3.0**
Maximum		**2.1**	**0.2**	**0.3**	**6.3**	**28.2**	**27.6**	**74.8**	**9.00**	**61.4**	**86.8**	**4.02**	**16.8**	**3.8**	**3.0**
Mean		**1.6**	**0.1**	**0.2**	**3.0**	**7.9**	**18.6**	**48.3**	**3.51**	**41.0**	**39.5**	**2.56**	**8.3**	**2.6**	**3.0**
TRAPEZOIDAL															
T32	13-May-08	2.3	0.3	0.73	10.1	123.2	89.2	8.0	4.83	10.2	23.6	1.73	8.1	2.3	1.8
	6-Jun-08	2.5	0.3	0.62	5.7	59.2	76.8	12.5	2.00	34.8	62.3	0.94	15.5	3.6	
	11-Jun-08	2.4	0.4	0.90	14.8	222.4	85.4		2.09	68.6	102.5	7.51	31.0	7.4	
	16-Jun-08	2.3	0.3	0.64	7.0	74.6	87.7	21.0	1.08	29.0	25.4	2.97	9.4	2.3	
	27-Jun-08	2.4	0.3	0.72	6.9	82.2	71.0	5.4	0.73	22.9	22.3	1.37	9.0	2.7	
Minimum		**2.3**	**0.3**	**0.6**	**5.7**	**59.2**	**71.0**	**5.4**	**0.73**	**10.2**	**22.3**	**0.94**	**8.1**	**2.3**	
Maximum		**2.5**	**0.4**	**0.9**	**14.8**	**222.4**	**89.2**	**21.0**	**4.83**	**68.6**	**102.5**	**7.51**	**31.0**	**7.4**	
Mean		**2.4**	**0.3**	**0.7**	**8.9**	**112.3**	**82.0**	**11.7**	**2.15**	**33.1**	**47.2**	**2.91**	**14.6**	**3.6**	
ALL SITES															
Minimum		**1.3**	**0.1**	**0.1**	**0.3**	**0.0**	**8.5**	**5.4**	**0.73**	**10.2**	**8.5**	**0.49**	**4.6**	**2.1**	**1.8**
Maximum		**5.6**	**0.5**	**2.8**	**15.2**	**704.9**	**89.2**	**74.8**	**9.00**	**462.6**	**173.0**	**11.83**	**342.0**	**35.4**	**3.0**
Mean		**2.6**	**0.2**	**0.6**	**6.3**	**98.1**	**40.5**	**34.3**	**3.15**	**75.4**	**55.8**	**3.64**	**33.8**	**5.3**	**2.4**

Table C. Summary of weekly data for environmental parameters at the reference site in the River Raisin Watershed, Michigan.

	Date	Width (m)	Depth (m)	Cross Section (m^2)	Velocity (m min^{-1})	Q (L s^{-1})	% of incident PAR reaching stream surface	% of bottom covered by submerged vegetation	Chlorophyll *a* (µg L^{-1})	TP (µg L^{-1})	NH_4 (µg L^{-1})	NO_3 (mg L^{-1})	TSS (mg L^{-1})	SOM (mg L^{-1})	% OM in sediment
REFERENCE															
R7	15-May-08	4.6	0.3	1.6595	2.7	71.6	63.3	4.9	4.08	44.8	126.0	0.93	43.0	5.9	2.0
	5-Jun-08	3.8	0.3	1.22	1.7	34.4	62.1	1.4	8.46	82.0	153.4	0.65	9.6	2.9	
	12-Jun-08	4.3	0.3	1.38	2.4	53.5	4.9		7.56	110.8	137.7	2.19	15.8	3.4	
	18-Jun-08	4.0	0.2	1.04	1.3	22.8	16.6	1.9	3.09	95.3	78.9		12.4	3.2	1.3
	25-Jun-08	4.0	0.2	1.08	1.4	25.6	4.8	0.0	11.51	89.3	47.6		16.2	3.5	
	30-Jun-08	5.3	0.3	1.98	6.0	175.5	8.1		5.92	217.9	78.9		74.0	11.3	
Minimum		**3.8**	**0.2**	**1.0**	**1.3**	**22.8**	**4.8**	**0.0**	**3.09**	**44.8**	**47.6**	**0.65**	**9.6**	**2.9**	**1.3**
Maximum		**5.3**	**0.3**	**2.0**	**6.0**	**175.5**	**63.3**	**4.9**	**11.51**	**217.9**	**153.4**	**2.19**	**74.0**	**11.3**	**2.0**
Mean		**4.3**	**0.3**	**1.4**	**2.6**	**63.9**	**26.6**	**2.0**	**6.77**	**106.7**	**103.8**	**1.26**	**28.5**	**5.0**	**1.7**
REFERENCE															
R10	15-May-08	3.9	0.3	1.06	9.0	156.6	58.6	11.8	2.71	33.5	82.9	0.29	68.5	7.0	2.7
	5-Jun-08	3.4	0.3	0.79	6.4	76.0	22.3	23.5	1.66	89.0	86.8	0.29	7.5	3.1	
	12-Jun-08	3.9	0.3	1.15	11.5	217.7	26.9		8.63	110.3	73.1	1.06	44.6	9.5	
	18-Jun-08	3.4	0.3	0.80	6.4	82.1	43.0	22.6	10.43	159.3	145.6	0.42	16.0	4.9	2.2
	25-Jun-08	3.6	0.3	0.95	3.5	54.8	46.9	19.3	2.91	166.2	259.3	0.33	11.8	5.5	
	30-Jun-08	4.0	0.4	1.45	13.7	329.3	36.4		4.87	70.0	31.9		27.2	6.1	
Minimum		**3.4**	**0.3**	**0.8**	**3.5**	**54.8**	**22.3**	**11.8**	**1.66**	**33.5**	**31.9**	**0.29**	**7.5**	**3.1**	**2.2**
Maximum		**4.0**	**0.4**	**1.4**	**13.7**	**329.3**	**58.6**	**23.5**	**10.43**	**166.2**	**259.3**	**1.06**	**68.5**	**9.5**	**2.7**
Mean		**3.7**	**0.3**	**1.0**	**8.4**	**152.8**	**39.0**	**19.3**	**5.20**	**104.7**	**113.2**	**0.48**	**29.3**	**6.0**	**2.4**
REFERENCE															
R37	15-May-08	4.4	0.5	1.98	19.0	620.3	39.4		5.51	25.4	16.0	0.14	37.0	7.3	1.9
	9-Jun-08	4.3	0.3	1.12	11.3	209.5	43.3	0.0	3.09	28.6	42.9	0.16	34.8	7.5	
	11-Jun-08	4.6	0.4	1.62	17.7	475.2	18.5		3.68	57.4	36.7	0.15	50.4	9.8	
	17-Jun-08	4.4	0.2	0.99	7.8	127.4	3.4	0.0	1.20	24.1	25.7	0.16	13.2	3.3	
	27-Jun-08	4.3	0.2	0.95	8.2	126.9	13.5	0.0	1.38	19.5	18.4	0.16	8.0	2.6	
Minimum		**4.3**	**0.2**	**0.9**	**7.8**	**126.9**	**3.4**	**0.0**	**1.20**	**19.5**	**16.0**	**0.14**	**8.0**	**2.6**	
Maximum		**4.6**	**0.5**	**2.0**	**19.0**	**620.3**	**43.3**	**0.0**	**5.51**	**57.4**	**42.9**	**0.16**	**50.4**	**9.8**	
Mean		**4.4**	**0.3**	**1.3**	**12.8**	**311.9**	**23.6**	**0.0**	**2.97**	**31.0**	**27.9**	**0.15**	**28.7**	**6.1**	
ALL SITES															
Minimum		**3.4**	**0.2**	**0.8**	**1.3**	**22.8**	**3.4**	**0.0**	**1.20**	**19.5**	**16.0**	**0.14**	**7.5**	**2.6**	**1.3**
Maximum		**5.3**	**0.5**	**2.0**	**19.0**	**620.3**	**63.3**	**23.5**	**11.51**	**217.9**	**259.3**	**2.19**	**74.0**	**11.3**	**2.7**
Mean		**4.1**	**0.3**	**1.2**	**7.6**	**168.2**	**30.1**	**7.8**	**5.10**	**83.7**	**84.8**	**0.53**	**28.8**	**5.7**	**2.0**

Table D. Correlation matrix for the reference metabolism site. (ER = ecosystem respiration, GPP = gross primary productivity, TP = total phosphorus, NH_4 = ammonia, NO_3 = nitrate, TSS = total suspended solids, OSM = organic suspended matter). Bolded values were those for which correlation scatterplots were made. Underlined values indicate significant correlations.

	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**	**% of incident PAR reaching stream surface**	**Chlorophyll *a* ($ug\ L^{-1}$)**	**TP ($ug\ L^{-1}$)**	**NH_4 ($ug\ L^{-1}$)**	**NO_3 ($mg\ L^{-1}$)**	**TSS ($mg\ L^{-1}$)**	**SOM ($mg\ L^{-1}$)**
ER ($g\ O_2\ m^{-2}\ day^{-1}$)	1.00								
GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	**0.59**	1.00							
% of incident PAR reaching stream surface	**0.88**	0.41	1.00						
Chlorophyll *a* ($ug\ L^{-1}$)	**0.90**	**0.85**	0.74	1.00					
TP ($ug\ L^{-1}$)	0.35	0.06	-0.01	0.32	1.00				
NH_4 ($ug\ L^{-1}$)	0.19	-0.53	0.25	-0.04	0.55	1.00			
NO_3 ($mg\ L^{-1}$)	-0.58	**-0.99**	-0.36	-0.82	-0.07	0.58	1.00		
TSS ($mg\ L^{-1}$)	0.78*	0.43	0.55	0.78	0.80	0.51	-0.40	1.00	
SOM ($mg\ L^{-1}$)	**0.79**	0.38	0.58	0.76	0.80	0.55	-0.35	1.00	1.00

*TSS was highly correlated with OSM so only OSM was plotted against metabolism variables.

Table E. Correlation matrix for the trapezoidal metabolism site. (ER = ecosystem respiration, GPP = gross primary productivity, TP = total phosphorus, NH_4 = ammonia, NO_3 = nitrate, TSS = total suspended solids, OSM = organic suspended matter). Bolded values were those for which correlation scatterplots were made. Underlined values indicate significant correlations.

	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**	**% of incident PAR reaching stream surface**	**% of bottom covered by submerged vegetation**	**Chlorophyll *a* ($ug\ L^{-1}$)**	**TP ($ug\ L^{-1}$)**	**NH_4 ($ug\ L^{-1}$)**	**NO_3 ($mg\ L^{-1}$)**	**TSS ($mg\ L^{-1}$)**	**SOM ($mg\ L^{-1}$)**
ER ($g\ O_2\ m^{-2}\ day^{-1}$)	1.00									
GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	**0.58**	1.00								
% of incident PAR reaching stream surface	0.21	0.09	1.00							
% of bottom covered by submerged vegetation	<u>**-0.86**</u>	0.70	0.51	1.00						
Chlorophyll *a* ($ug\ L^{-1}$)	0.29	-0.46	0.58	-0.29	1.00					
TP ($ug\ L^{-1}$)	<u>**0.70**</u>	<u>**0.97**</u>	0.05	0.52	-0.32	1.00				
NH_4 ($ug\ L^{-1}$)	<u>**0.78**</u>	<u>**0.82**</u>	0.08	0.14	-0.04	0.94	1.00			
NO_3 ($mg\ L^{-1}$)	<u>**0.80**</u>	<u>**0.88**</u>	0.41	0.74	-0.06	0.86	0.77	1.00		
TSS ($mg\ L^{-1}$)	0.84*	0.88*	0.12	0.17	-0.08	0.96	0.98	0.87	1.00	
SOM ($mg\ L^{-1}$)	<u>**0.88**</u>	<u>**0.86**</u>	0.08	-0.12	-0.08	0.95	0.96	0.88	0.99	1.00

*TSS was highly correlated with OSM so only OSM was plotted against metabolism variables.

Table F. Correlation matrix for the benched metabolism site. (ER = ecosystem respiration, GPP = gross primary productivity, TP = total phosphorus, NH_4 = ammonia, NO_3 = nitrate, TSS = total suspended solids, OSM = organic suspended matter). Bolded values were those for which correlation scatterplots were made. Underlined values indicate significant correlations.

	ER ($g\ O_2\ m^{-2}\ day^{-1}$)	**GPP ($g\ O_2\ m^{-2}\ day^{-1}$)**	**% of incident PAR reaching stream surface**	**% of bottom covered by submerged vegetation**	**Chlorophyll *a* ($ug\ L^{-1}$)**	**TP ($ug\ L^{-1}$)**	**NH_4 ($ug\ L^{-1}$)**	**NO_3 ($mg\ L^{-1}$)**	**TSS ($mg\ L^{-1}$)**	**SOM ($mg\ L^{-1}$)**
ER ($g\ O_2\ m^{-2}\ day^{-1}$)	1.00									
GPP ($g\ O_2\ m^{-2}\ day^{-1}$)	**0.94**	1.00								
% of incident PAR reaching stream surface	0.31	0.01	1.00							
% of bottom covered by submerged vegetation	-0.35	0.29	-0.93	1.00						
Chlorophyll *a* ($ug\ L^{-1}$)	-0.06	-0.38	0.86	-0.99	1.00					
TP ($ug\ L^{-1}$)	**0.77**	**0.61**	0.56	-0.69	0.34	1.00				
NH_4 ($ug\ L^{-1}$)	**0.87**	**0.93**	0.19	0.10	-0.27	0.64	1.00			
NO_3 ($mg\ L^{-1}$)	**0.87**	**0.81**	0.07	-0.69	-0.12	0.71	0.59	1.00		
TSS ($mg\ L^{-1}$)	-0.08	-0.40	0.82	-0.97	0.99	0.36	-0.32	-0.08	1.00	
SOM ($mg\ L^{-1}$)	-0.05	-0.37	0.81	-0.96	0.99	0.31	-0.32	-0.05	0.99	1.00