Ecological Indicators 5 (2005) 243–252

ECOLOGICAL INDICATORS

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Stream diurnal dissolved oxygen profiles as indicators of in-stream metabolism and disturbance effects: Fort Benning as a case study

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Accepted 22 March 2005

Abstract

We investigated whether two characteristics of stream diurnal dissolved oxygen profiles, the daily amplitude and maximum value of the dissolved oxygen saturation deficit, are useful indicators of stream metabolism and the effects of catchment-scale disturbances. The study was conducted at the U.S. Army's Fort Benning installation where vegetation loss and high rates of erosion from intensely used training areas and unpaved roads have resulted in extensive sedimentation in some streams. Diurnal profiles of dissolved oxygen were measured in 10 second-order streams draining catchments which exhibited a range of disturbance levels. Rates of gross primary production (GPP) and total ecosystem respiration (*R*) per unit surface area were determined for each stream using the single-station diurnal dissolved oxygen change method with direct measurement of air–water oxygen exchange rates. The daily amplitude of the diurnal dissolved oxygen deficit profile was highly correlated with daily rates of GPP, and multiplying the daily amplitude by average stream depth to account for differences in water volume did not improve the correlation. The daily maximum dissolved oxygen deficit was highly correlated with daily rates of *R*, and multiplying by average stream depth improved the correlation. In general, these indicators of stream metabolism declined sharply with increasing catchment disturbance level, although the indicators of *R* showed a more consistent relationship with disturbance level than those of GPP. Our results show that the daily amplitude and maximum value of diurnal dissolved oxygen deficit profiles are good indicators of reach-scale rates of metabolism and the effects of catchment-scale disturbance on these metabolism rates. At Fort Benning, and presumably at other military installations, they are useful tools for evaluating trends in impacts from military training or rates of recovery following restoration activities.
Published by Elsevier Ltd.

Keywords: Stream; Diurnal dissolved oxygen; Metabolism; Indicator; Primary productivity; Respiration; Military

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1470-160X/$ – see front matter. Published by Elsevier Ltd.
doi:10.1016/j.ecolind.2005.03.004

1. Introduction

Stream measurements can be good indicators of ecological conditions at the scale of entire watersheds because of the spatially integrating effects of drainage water emerging as streamflow. Various stream chemistry indicators have been used to identify changes in ecosystem function at the watershed scale. For example, stream nitrate concentrations have been used to infer various perturbations of terrestrial nutrient cycling resulting from deforestation (Bormann and Likens, 1979), insect defoliation (Swank, 1988), N deposition effects (Aber et al., 2003), and climate perturbations (Mitchell et al., 1996; Aber et al., 2002).

Measurements of stream metabolism, if made over entire stream reaches, are potentially good indicators of ecological disturbance at the watershed scale because metabolism is influenced by a combination of physical, chemical, and biological characteristics of streams which, in turn, are affected by drainage water transport from throughout the catchment. However, measurements of reach-scale stream metabolism are laborious, even with automated dissolved oxygen monitors, because they require good estimates or direct measurements of air–water gas exchange and involve many computations (Marzolf et al., 1994; McCutchan et al., 1998; Mulholland et al., 2001). Diurnal profiles of dissolved oxygen concentration contain much of the information needed for stream metabolism determinations and may be useful as indicators of stream metabolism.

Stream metabolism indices based on characteristics of diurnal dissolved oxygen profiles have been previously proposed by several investigators. Chapra and Di Toro (1991) developed the ‘‘delta method’’ which uses the average dissolved oxygen deficit, the daily range in the deficit, and the time of minimum deficit in a graphical approach to estimate respiration rate, gross primary production rate, and reaeration rate, respectively. In a simplification of the delta method, Wang et al. (2003) proposed the ‘‘extreme value method’’ in which the maximum and minimum dissolved oxygen deficits are used to estimate stream metabolism rates. However, both the delta and extreme value methods used in these studies provided volumetric-based estimates of metabolism rates rather than rates per unit of stream surface area, and neither has been evaluated against metabolism rates determined using the diurnal dissolved oxygen approach with direct measurements of the air–water oxygen exchange rate using volatile gas tracers (Marzolf et al., 1994).

Our objectives in this study were to evaluate whether two simple characteristics of diurnal dissolved oxygen profiles, the daily amplitude and maximum value of the dissolved oxygen saturation deficit profile, are useful indicators of: (1) reach-scale stream metabolism rates per unit area and (2) effects of catchment-scale disturbance to stream ecosystems. We evaluated two versions of each of these potential indicators. The first version was essentially the same as used in the extreme value method of Wang et al. (2003)—the daily amplitude and maximum value of the diurnal dissolved oxygen deficit profile. The second version involved multiplying both the daily amplitude and maximum value by average stream water depth to account for the effect of differences in stream water volume.

The study was conducted at the U.S. Army's Fort Benning installation where vegetation loss and high rates of erosion from intensively used training areas and unpaved roads have resulted in extensive sedimentation in some streams. In a related paper, we show that these catchment-scale disturbances have resulted in reduction in stream gross primary productivity and total ecosystem respiration rates during some seasons (Houser et al., in press). In this paper, we evaluate whether two easily measured characteristics of diurnal dissolved oxygen profiles can be used as surrogate measures or indicators of stream metabolism rates to identify effects of catchment-scale disturbances on important stream functions.

2. Study site

Fort Benning is a U.S. Army infantry training base occupying 73,503 ha in central-western GA, USA. The climate is humid and mild with rainfall occurring regularly throughout the year and averaging 105 cm annually. Fort Benning is located primarily within the Sand Hills and Southern Hilly Gulf Coastal Plain Level IV ecoregions of the southeastern USA (Griffith et al., 2001). Much of the base is forested and dominated by mixed longleaf (*Pinus palustris*), loblolly (*Pinus taeda*), and shortleaf pine (*Pinus echinata*) communities with some areas of mixed hardwoods dominated by oak (Elliot et al., 1995). Sandy or sandy clay loam soils cover most of the base (Elliot et al., 1995). Streams are relatively low gradient (1–2.5% slope) and often are meandering within broad floodplains. Floodplain vegetation is primarily mesic hardwoods dominated by water oak (*Quercu nigra*), sweetgum (*Liquidamber styraciflua*), and swamp tupelo (*Nyssa sylvatica* var. biflora) (Cavalcanti, 2004). Streams have generally sandy bottoms but often contain roots of riparian vegetation and considerable amounts of woody debris and deposits of fine organic matter, particularly if catchments are relatively undisturbed.

Fort Benning contains numerous areas ranging from several to hundreds of hectare in size used intensively for military training activities involving tracked and other vehicle maneuvering (Dale et al., 2002). These areas, which are primarily in the upland portions of catchments, have become denuded of most vegetation and the soils are highly disturbed and subject to extensive erosion. Ephemeral drainages convey the eroded sediments to perennial streams where subsequent sedimentation has resulted in burial of organic matter and highly unstable, shifting bottom sediments low in organic matter content. In addition, unpaved roads also experience high rates of erosion and contribute large quantities of eroded sediments to streams.

3. Methods

Ten second-order streams draining catchments with a range of disturbance levels were chosen for study (Fig. 1). Total catchment area and disturbance level in each catchment were quantified using digital elevation maps for Fort Benning (http://sempdata.wes.army.mil) and GIS-based land cover maps developed from satellite imagery (Olsen et al., in press). Catchment

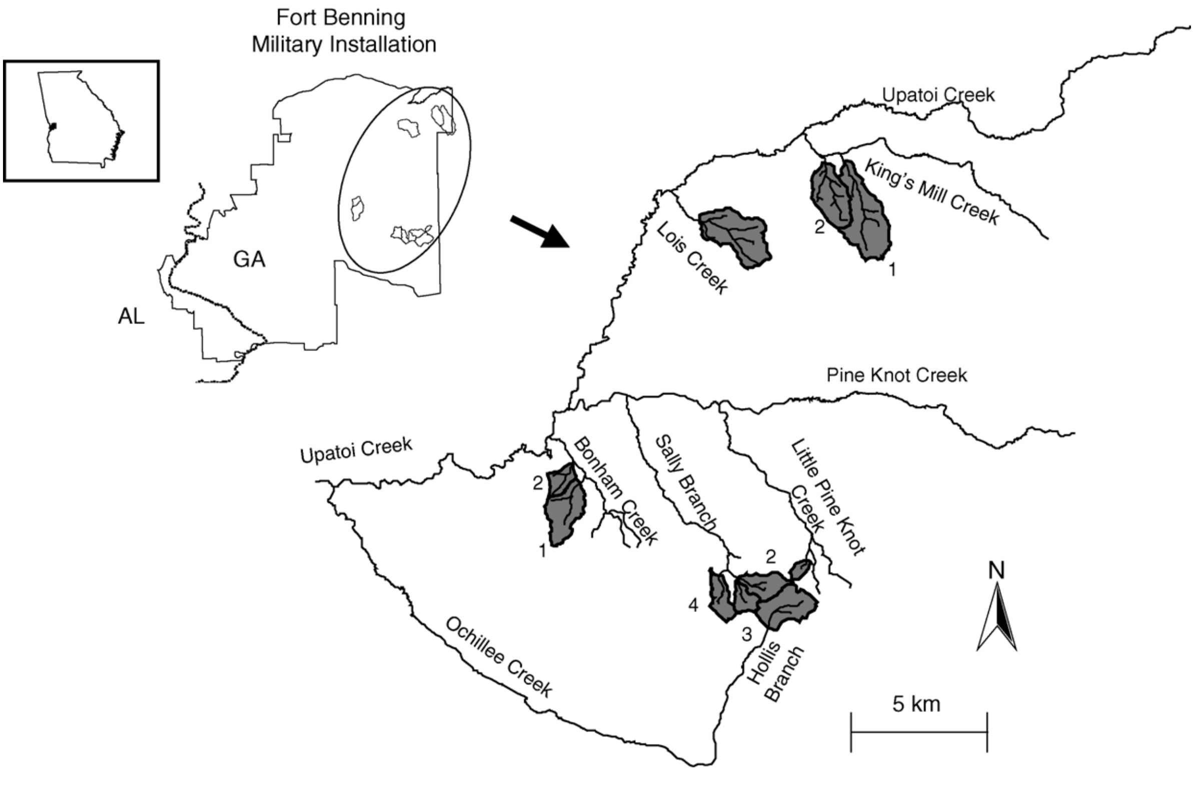

Fig. 1. Map of Fort Benning showing location of the study catchments.

disturbance level was defined as the sum of the proportion of the catchment consisting of bare ground on slopes >3% and the proportion of the catchment covered by unpaved roads (see Maloney et al., in press for additional details). Except for four highly disturbed catchments, disturbance levels for all 249 second-order stream catchments at Fort Benning span a range of 0–17%. The 10 catchments included in this study spanned much of this available disturbance gradient with disturbance levels ranging from 1.8 to 13.6%.

Reach-scale rates of gross primary production (GPP) and total ecosystem respiration (*R*) were determined for each stream using the open-channel, single-station diurnal dissolved oxygen change method (Owens, 1974; Bott, 1996). YSI model 6000 or 600 series sondes equipped with YSI model 6562 dissolved oxygen probes were deployed for 2–3 week periods in a well mixed point in each stream during the period from 8 April to 12 May 2002, recording dissolved oxygen concentrations and water temperatures at 15-min intervals. The sondes were deployed in only five streams at any one time due to equipment limitations. To reduce variability resulting from weather-related effects, data only for those dates with relatively high values of daily photosynthetically active radiation (>70% of the seasonal maximum value as measured at a meteorological station within 10 km of the streams) and discharge values similar to those during sonde deployment were used in the analysis.

At the time of sonde deployment, discharge and air–water gas exchange rate were measured in each stream by a simultaneous, steady-state injection of a conservative (NaCl) and volatile (propane) tracer to stream water (Marzolf et al., 1994). Specific conductance and dissolved propane concentrations were measured at two stations. The upper station was about 10–20 m downstream from the injection to ensure complete mixing of the injected solution and gas. The downstream station was located 40–100 m downstream from the upper station, depending on the water velocity. Specific conductance was measured using a YSI model 30 conductivity meter. Stream discharge was calculated from the difference between pre-injection and steady-state values of specific conductance in the stream, the specific conductance of the injection solution, and the injection rate. Average water travel time for each study reach was determined from the time of maximum slope of the rate of increase in specific conductance at each station. Average water velocity was calculated from the water travel time and the distance between sampling stations. Average wetted width of the stream was determined by measuring widths every 5 m between the two sampling stations. Average water depth was computed as discharge divided by the product of average wetted width and average water velocity.

For dissolved propane measurements, six samples were collected at each station by drawing 6 mL of stream water into a syringe and injecting the water into pre-evacuated 8 mL vials. The headspace in the vials was then equilibrated with the atmosphere and the vials returned to the laboratory for analysis. Propane concentrations in subsamples of headspace gas

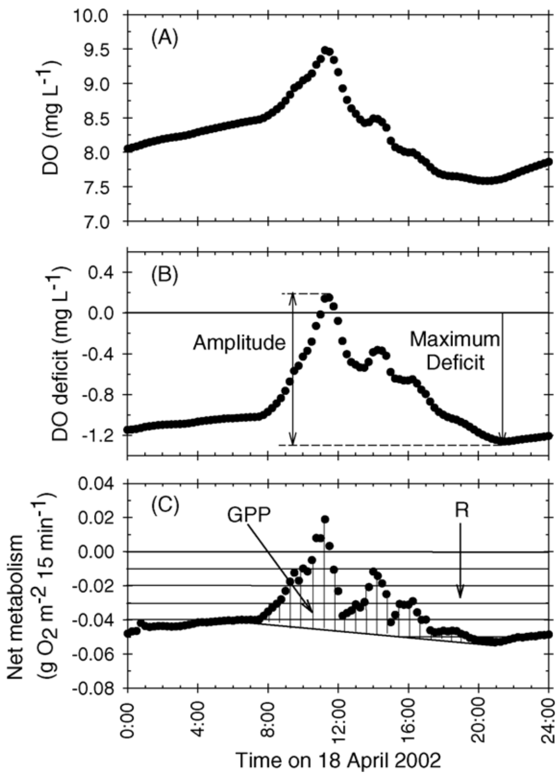

Fig. 2. Diurnal profiles (1-h running averages) of (A) dissolved oxygen concentration (DO), (B) dissolved oxygen saturation deficit showing the amplitude and maximum absolute value of the deficit profile, and (C) net metabolism rate showing the area representing gross primary production (GPP, vertical lines) and total ecosystem respiration (*R*, horizontal lines). Data are from 18 April 2002.

(80 μL) were determined within 1–2 days of collection by gas chromatography using a Hewlett Packard Model 5890 Series II with a Poraplot Q column and flame ionization detector. Air–water exchange rate of propane was calculated as the first-order rate constant of propane concentration decline from the upper to the lower station, corrected for dilution due to increase in discharge, and divided by water travel time between the two stations. Propane gas exchange rates were then converted to oxygen gas exchanges rates by multiplying by a factor of 1.39 (Rathbun et al., 1978).

Stream water pH, dissolved organic carbon (DOC), and nutrient concentrations were also determined at the time of sonde deployment in each stream. Methods for these analyses are presented in Maloney et al. (in press).

Rates of net dissolved oxygen change due to metabolism (net metabolism) were determined as the difference between successive 15-min measurements corrected for air–water oxygen exchange between measurements and average water depth. The rate of air–water oxygen exchange was calculated as the product of the rate coefficient (determined from the NaCl/propane injections) and the observed percent dissolved oxygen saturation using barometric pressure data from a meteorological station within 10 km of the stream and converted to stream elevation. Nighttime *R* was calculated as the sum of the net metabolism measurements during the night. Daytime *R* was determined by interpolating between respiration rates measured 1 h before dawn and 1 h after dusk. Total daily *R* was the sum of nighttime and daytime *R* over 24 h periods (from midnight to midnight). Daily GPP was the sum of the differences between the interpolated daytime respiration rates and the observed net metabolism (see Fig. 2 and Marzolf et al., 1994 for a more complete explanation of the calculations of daily GPP and *R*).

We calculated the daily amplitude and maximum absolute value for each of the diurnal dissolved oxygen saturation deficit profiles as indices of daily GPP and *R*, respectively. We used 1-h running average values of the dissolved oxygen saturation deficit for these calculations to avoid bias by isolated high or low measurements. We also multiplied the daily amplitude and maximum values by average water depth to provide a second version of each of these indices that takes into account differences in water volume. Average values of these four indices were calculated for each stream over the study period and compared to average values of daily GPP and *R* as well as to catchment disturbance levels to determine their

Table 1
Stream and catchment characteristics

Stream	Abbreviation	Catchment area (ha)	Disturbance level (%)	Channel gradient (%)	Discharge (L/s)	Average water depth (cm)	Reaeration rate (min^{-1})	Specific conductance (μS/cm)	pH	DOC (mg/L)	DIN (μg N/L)	SRP (μg P/L)
Kings Mill Creek Tributary 2	KM2	231	1.8	1.00	22.2	19.1	<0.01	24.4	4.8	2.5	2.7	2.2
Bonham Creek Tributary 2	BC2	74.9	3.2	2.67	9.9	12.9	0.020	22.8	4.9	3.4	16.6	3.1
Lois Creek	LC	332	3.7	1.69	19.1	17.1	0.020	19	4.87	2.8	0.7	2.2
Kings Mill Creek Tributary 1	KM1	369	4.6	0.83	55	20.8	0.026	16	4.97	3.7	27.2	1.8
Hollis Branch	HB	215	6.6	2.00	23.3	13	0.025	20.5	5.05	5.4	27.2	0.3
Sally Branch Tributary 2	SB2	123	8.1	2.31	15.2	4.2	0.044	21.7	6.03	2.7	36.7	0.3
Bonham Creek Tributary 1	BC1	210	10.5	1.67	18.5	18.1	0.012	26.1	4.55	3	7.2	2.4
Sally Branch Tributary 3	SB3	71.7	10.5	1.00	6.9	6.6	0.072	18	6.08	3.5	5.3	2.4
Little Pine Knot Tributary	LPK	33.1	11.3	5.10	7.2	7.1	0.087	13.4	5.22	2.7	31.7	1
Sally Branch Tributary 4	SB4	100	13.6	1.33	7.4	3.5	0.071	18.4	5.41	2.6	29.8	2.8

Data are from measurements made at the beginning of the period of dissolved oxygen measurements. Catchment area, disturbance level, and channel gradient are from Maloney et al. (in press).

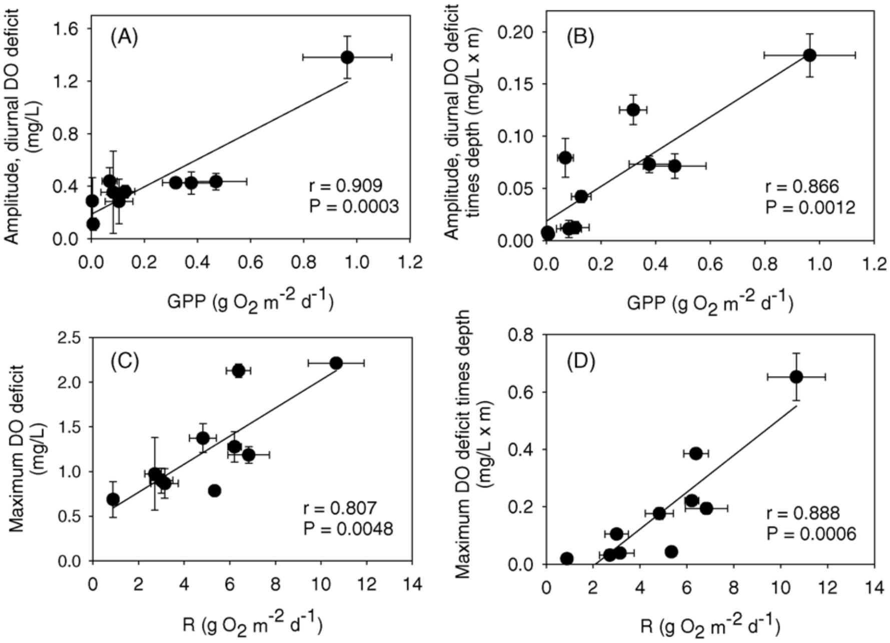

Fig. 3. Relationships between gross primary production rate (GPP) and (A) amplitude of the diurnal dissolved oxygen (DO) deficit profile and (B) amplitude of the diurnal DO deficit profile times average water depth. Also shown are relationships between total daily respiration rate (*R*) and (C) the maximum absolute value of the diurnal DO deficit profile and (D) the maximum absolute value of the diurnal DO deficit profile times average water depth. Data points are means for individual stations (*n* ranges from 3 to 11 dates per station) and error bars indicate one standard deviation. Pearson correlation coefficients and *P*-values are indicated on each plot.

usefulness as indicators of stream metabolism and response to disturbance.

4. Results

Stream and catchment characteristics, including disturbance levels, are given in Table 1. Catchments ranged in size from 33 to 369 ha and varied in discharge from 6.9 to 55 L/s. Streams ranged in pH from 4.8 to 6.1 and ionic strength, dissolved organic carbon, and nutrient concentrations were relatively low in all streams.

The dissolved oxygen profile for site BC2 on 18 April 2002 shows the typical diurnal pattern observed in these streams (Fig. 2A). The diurnal pattern in the dissolved oxygen saturation deficit showing the amplitude and maximum deficit is shown in Fig. 2B. Rates of GPP and *R* are calculated from the areas under the daytime net metabolism peak and that between zero and the net metabolism curve, respectively (Fig. 2C).

Correlations between both versions of the amplitude-based indicator and rates of GPP per unit surface area were high (Fig. 3A and B). Similarly, correlations between both versions of the maximum deficit-based indicator and *R* per unit surface area were also high (Fig. 3C and D). It appears that accounting for water depth provides a slightly improved indicator for *R*, but not for GPP.

In general, all of the indicators of metabolism declined with increasing catchment disturbance level (Fig. 4). However, the relationship between the daily amplitude and disturbance level was very weak, with disturbance level explaining only 26% of the variation in this version of this indicator (Fig. 4A). Relationships between the daily amplitude times water depth and disturbance level and between both versions of the daily maximum deficit indicator and disturbance level were considerably stronger (Fig. 4B, C, and D). There was one stream (BC1), however, that appeared to be an outlier in the overall pattern, with considerably higher values for the metabolism indicators than expected for its catchment disturbance level. Although the catch-

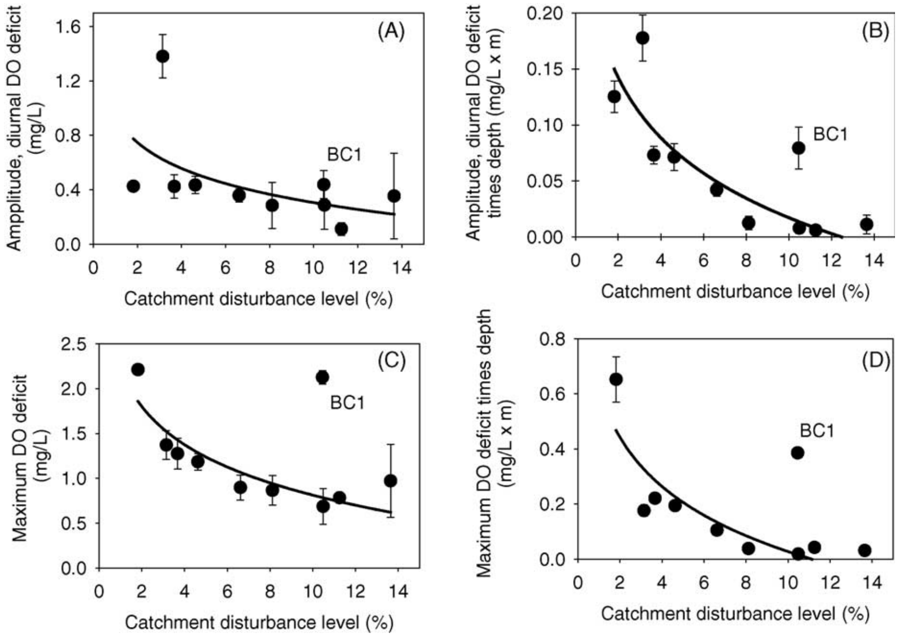

Fig. 4. Relationships between catchment disturbance level and (A) average amplitude of the diurnal dissolved oxygen (DO), (B) average amplitude of the diurnal DO deficit times average water depth, (C) average maximum absolute value of the diurnal DO deficit, and (D) average maximum absolute value of the diurnal DO deficit times average water depth. Lines of best fit of the data in each panel to an exponential model ($Y = Y_0 - A \times \ln X$) are shown with BC1 excluded. This model explained 26% of the variation in panel (A), 76% of the variation in panel (B), 80% of the variation in panel (C), and 77% of the variation in panel (D).

ment of this stream has a relatively high disturbance level, the stream is bordered by a broad forested floodplain and the channel morphology appears to be relatively undisturbed. Excluding BC1 from the analysis, exponential models based on catchment disturbance level explained 76–80% of the variation in the amplitude times water depth and both versions of the maximum deficit indicator. With the exception of BC1, average values of indicators adjusted for water depth were very low for streams in catchments with disturbance levels of 8% or more (Fig. 4B and D).

5. Discussion

Our results show that diurnal profiles of the dissolved oxygen saturation deficit reflect the rates of in-stream metabolism (GPP and *R*) and are useful indicators for comparisons of metabolism among streams. The maximum absolute value of the dissolved oxygen deficit (usually occurring early in the night-time period) is influenced primarily by *R* and air–water exchange of oxygen, whereas the minimum value of the dissolved oxygen saturation deficit (usually occurring in late morning or early afternoon) represents a balance between GPP, *R*, and air–water exchange. Thus, the daily amplitude of the diurnal deficit profile provides an index of daily GPP and the maximum absolute value of the deficit profile is an index of daily *R* (Fig. 2).

Most of the metabolism within small streams and rivers is associated with the bottom or stationary substrata (e.g., woody debris); however, determination of metabolism rates is usually based on measurements of dissolved oxygen concentration changes in the overlying water. Therefore, we had anticipated that accounting for differences in water depth would improve correlations between the two oxygen profile-based indicators and rates of metabolism per unit stream area. However, multiplying by average water depth resulted in only a small improvement in the correlation between the maximum deficit and *R* and a slightly poorer correlation between daily amplitude and GPP (Fig. 3).

The apparent lack of effect of differences in water depth on the metabolism indicators may be because air–water exchange of oxygen is also a surface process and tends to counteract the effect of metabolism on stream water dissolved oxygen concentrations. The primary factors regulating air–water gas exchange rates are surface turbulence and volumetric water mixing. Differences in surface turbulence among our streams were likely small because stream channel gradients were low and not greatly different among the streams (Table 1). Rates of air–water oxygen exchange (expressed as volumetric turnover rates in units of time^{-1}) were negatively correlated with average stream water depths ($r = -0.82$, $P = 0.004$, Table 1). Thus, although a given rate of metabolism would be expected to result in smaller changes in stream water dissolved oxygen concentration in a deeper stream, the volumetric air–water exchange rate of oxygen would also be lower in a deeper stream and counteract, to some degree, the effect of water depth on metabolism.

Our results also show that metrics based on diurnal profiles of the dissolved oxygen saturation deficit in streams are useful indicators of catchment-scale disturbance. Although the daily amplitude of the diurnal oxygen deficit was poorly related to catchment disturbance level, when multiplied by average water depth the relationship between this metric and disturbance level was relatively strong (Fig. 4B). The relationship between the daily maximum deficit value and disturbance level was quite strong with and without the inclusion of average water depth in the calculation of this indicator (Fig. 4C and D).

The reason for the contrast in results for the two versions of the disturbance indicator based on the daily amplitude is not clear, particularly when considering that both versions of this indicator were shown to be relatively good indicators of stream GPP. This apparent contradiction may be a result of the relatively low values of GPP in these streams. In all but one stream, GPP was <0.5 g O_2 m^{-2} day^{-1} which falls in the lower part of the range of values reported for other small streams in the intersite study of Mulholland et al. (2001). Houser et al. (in press) reported a significant negative relationship between GPP and catchment disturbance level only during spring of 2002 during 2 years of quarterly measurements in these Fort Benning streams. Values of R were generally an order of magnitude higher than GPP and Houser et al. (in press) reported significant negative relationships between R and catchment disturbance level during all seasons but autumn. Thus, diurnal oxygen profile metrics related to R (i.e., daily maximum deficit with and without inclusion of water depth) appear to be much stronger indicators of the effect of catchment disturbance at Fort Benning than metrics related to GPP.

The stream diurnal dissolved oxygen profile metrics are good indicators of catchment-scale disturbance at Fort Benning because the major disturbances to streams at Fort Benning are primarily a result of the effects of increased runoff and erosion from denuded lands in upland portions of catchments rather than direct modification of stream conditions. The effect of upland erosion on streams is produced by sediment transport during storms and subsequent deposition in stream channels resulting in highly unstable streambeds of shifting sand. Maloney et al. (in press) reported that the amount of coarse woody debris exposed on the stream bottom and the organic matter content of streambed sediments are considerably lower in streams in more highly disturbed catchments at Fort Benning. In addition, the stream channels in many of the highly disturbed catchments appeared to be highly incised, likely the result of channel erosion and downcutting from higher stormflows due to reduced infiltration rates and greater surface runoff. Maloney et al. (in press) showed that stream storm hydrographs are steeper in more disturbed Fort Benning catchments. These effects on the physical characteristics of stream channels in more highly disturbed catchments would tend to reduce the available habitat for colonization and growth of algae and heterotrophic microbes which require stable substrata and organic matter, respectively. Finally, concentrations of soluble reactive phosphorus and DOC in stream water declined significantly with increasing disturbance levels in these catchments, presumably because of increased sorption by clay-rich stream sediments or reduced leaching losses from upland areas denuded of vegetation (Maloney et al., in press). These changes in the physical and chemical characteristics of streams resulting from upland disturbance would be expected to reduce rates of stream metabolism and our indicators of stream metabolism show this.

One stream, BC1, appeared to be an outlier in the pattern of reduced metabolism with increasing catchment disturbance (Fig. 4). Although the catchment of this stream has a relatively high disturbance level, the stream channel appears to be much less affected physically by the catchment disturbance. This stream has a very broad, forested floodplain and the abundance of coarse woody debris and the organic matter content of its sediments are more typical of the less disturbed catchments (Maloney et al., in press). The rates of metabolism (particularly *R*) in this stream are also more typical of streams in less disturbed catchments (Houser et al., in press).

This outlier suggests caution when using stream metabolism metrics as indicators of catchment-scale disturbance even within small regions. Local factors related to riparian vegetation (e.g., stature and density, leaf phenology, quantity, and quality of organic inputs) and floodplain/channel hydraulics can have large effects on stream metabolism. In a study investigating land use effects on stream metabolism, Young and Huryn (1999) showed that GPP was most influenced by characteristics that influenced the availability of light (e.g., shading by the riparian forest canopy, turbidity from disturbed catchments) and *R* was influenced primarily by characteristics controlling organic matter supply (e.g., riparian leaf input, organic content of sediments). Mulholland et al. (2001), in a study of stream metabolism across different biomes, found that light availability as regulated by riparian vegetation was the primary factor controlling GPP and the extent of surface/subsurface water exchange within stream channels was an important factor controlling *R*. These riparian and channel characteristics may over-ride or partially obscure effects of catchment-scale disturbances and must be considered when using stream metabolism indicators to assess disturbance impacts.

Our approach using the daily amplitude and maximum value of the diurnal dissolved oxygen deficit profile as indicators of stream metabolism supports the findings of Wang et al. (2003) and earlier those of Chapra and Di Toro (1991). Wang et al. (2003) termed their approach the extreme value method and used it to show impacts of land use change on stream metabolism. They reported that rates of GPP and *R* derived from these indicators were higher in an agricultural catchment stream than a stream in an urbanized catchment. Our results expand on these earlier studies by documenting the strong relationship between these indicators and simultaneous measurements of reach-scale rates of GPP and *R* per unit surface area in streams. Our results further show that these diurnal oxygen profile metrics can be good indicators of catchment-scale disturbance because stream metabolism is influenced by physical, chemical, and biological characteristics of streams which are, in turn, affected by drainage water transport from all portions of the catchment. With the availability of relatively low-cost, data-logging, field dissolved oxygen monitors, these indicators are considerably easier to measure than rates of stream metabolism which require good estimates of air–water gas exchange and involve many computations. At Fort Benning and other military installations, they provide a useful tool for evaluating trends in impacts from military training or rates of recovery following restoration activities.

Acknowledgements

We would like to thank the personnel at the Fort Benning Military Reservation for permitting regular visits to the reservation, and particularly Hugh Westbury for arranging access to our field sites on the reservation. Pete Swiderek and Gary Hollon provided scientific and logistical advice. Thanks to Michael Fuller, Richard Mitchell, and Gary Hollon for their assistance in the field. The manuscript has benefited greatly from the comments of Brian Roberts, Hal Balbach, and two anonymous reviewers. This project was supported by a grant from the U.S. Department of Defense's Strategic Environmental Research and Development Program (SERDP), Ecosystem Management Program (SEMP) to Oak Ridge National Laboratory (ORNL). Oak Ridge National Laboratory is managed by the University of Tennessee-Battelle LLC for the U.S. Department of Energy under contract DE-AC05-00OR22725.

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