1. **Project Title and EPA Grant Number:**

A Biological-Physical Numerical Simulation Model for the Investigation, Prediction,
and Management of Oxygen Production and Consumption in Long Island Sound: Data Analysis and
Model Formulation

Cooperative Agreement # LI-97101801-0

2. **Grantee Organization and Contact Name:**

Nicole Goebel
Ocean Sciences Department
University of California
Santa Cruz, CA 95062
ngoebel@ucsc.edu

James N. Kremer
Department of Marine Science
University of Connecticut
jkremer@uconn.edu

Chris Edwards
Ocean Sciences Department
University of California
Santa Cruz, CA   95064
cedwards@ucsc.edu

3. **Public Summary:**

Marked similarities in the along-sound gradients in measurements of primary production (Goebel et al. 2006), the frequency of hypoxia in the bottom waters (CT-DEP), and external loads and internal concentrations of nitrogen (NY-DEC & CT-DEP 2000) of Long Island Sound (LIS) support the idea that nitrogen driven increases in primary production result in the major source of organic matter that leads to summer hypoxic events in this estuarine system. Comprehensive management plans are currently in place to reduce nitrogen inputs to LIS, with the aim to reduce observed hypoxic events. Such managerial decisions call for an accurate, predictive model of LIS that is practicable for the management of this highly eutrophic, seasonally hypoxic system. Recent attempts to numerically model production in LIS (HydroQual 1996; HydroQual 1999) however, provide examples of complex, uncorroborated models that require tuning of a high number of parameters in order to obtain the desired output. Furthermore, support for these models relies on predictions of stocks (e.g. phytoplankton biomass) without confirmation of the underlying rates critical for an accurate, predictive model of processes (e.g primary production) that lead to reduced bottom water oxygen concentrations.

We have formulated an alternative model to the complex, highly parameterized models currently used to assess the reduction in nitrogen loads necessary to alleviate hypoxia in LIS. The model is simplified by reducing the number of state variables and parameters necessary to adequately describe the system, and the values and numbers of free parameters constrained with the use of consistent semi-empirical relationships to model the keystone processes thought to influence oxygen dynamics in LIS. Reduction in the complexity of our modeling approach allows for improved investigation and understanding of the complex relationship between oxygen production and consumption processes and low oxygen concentrations in LIS, that is often

masked by a high number of poorly-constrained parameters. Furthermore, such a simplistic model bolsters its utility as a management tool for evaluating present efforts to reduce nitrogen loads, hence hypoxia, in LIS.

This research has built upon the output of a previously EPA-funded study of Long Island Sound (LIS) "Water Column and Oxygen Production and Consumption: Measurement and Modeling (EPA Cooperative Agreement X-98164401)". In the previous study, a comprehensive set of measured rates of oxygen production and consumption throughout central and western LIS on 15 cruises during 2002 and 2003 enabled (1) characterization of temporal and spatial variations in primary production and community respiration and relationships to phytoplankton stocks and physico-chemical environmental variables (Goebel & Kremer In Press), and (2) annual measurements of primary production and the formulation of a primary production model specific to LIS (Goebel et al. 2006). This sub-model for primary production was then incorporated into a two-layer, time varying (0-dimensional) ecological model that also included export from the photic zone (upper layer) to the aphotic zone and benthos (lower layer), heterotrophic consumption in the water column and benthos, and benthic remineralization.

The primary objectives of the present study were to (1) implement this 0-d, two-layer ecological model in a 1-d vertically structured water column that varies with time, (2) refine, improve and test the consistency of this 1-d physical-ecosystem model, (3) assess the eco-physical model in a comparison of model output to measured concentrations of phytoplankton biomass (as chlorophyll), and rates of oxygen production (i.e. primary production) and consumption (i.e. respiration) in LIS, as well as published relationships between nitrogen loads and phytoplankton biomass and production (4) utilize the model to address management issues of hypoxia in the bottom waters of Long Island Sound by exploring the connection of nitrogen source loading with hypoxic events.

In a series of model runs that test the effects of increased external nitrogen loads to phytoplankton production and stocks (as chlorophyll) in LIS, we were able to demonstrate the consistency between modeled output of rates and stocks with and the cross-system relationship of increased chlorophyll stocks and rates of primary productivity with inputs of nitrogen (Nixon 1992). The cross-system comparison of Nixon's (1992) is independent of the formulation used to model primary production in our ecological physical model, hence comparison of our model output with this independent relationship serves as an independent corroboration of the accuracy of the formulation for primary production (and phytoplankton stocks) implemented in our model.

We also tested a modification of another semi-empirical formulation in our ecological-physical model, which predicts the average annual deposition of organic matter, hence oxygen demand (Borsuk et al. 2001) in LIS. In our model, we assumed that the primary source of carbon/oxygen demand, was from autochthonous (primary) production. Comparison of modeled daily rates of respiration in the aphotic portion of the water column over a series of model runs to measurements of water column respiration throughout LIS yielded a large inconsistency in the physical-ecological model. Measurements of oxygen consumption in LIS were 2-10 times larger than that calculated by the model. This discrepancy lead to further investigation of measured and modeled rates of oxygen consumption in LIS.

We determined that this disagreement between modeled outputs and measurements was not due to the accuracy of our field observations. Several comparisons of our observed data with the literature and other measured proxies for oxygen consumption in LIS indicate that our measurements are not only reasonable, but are also representative of the microbial community specific to the LIS ecosystem. Hence we felt confident that our comprehensive set of community respiration observations, as well as our detailed calculations of GPP (Goebel et al., 2006), in LIS are reasonable and representative of this highly productive system.

In a comparison of measured rates of community respiration (R_{cint}) and gross primary production (GPP_{int}) integrated over the depth of the water column, the majority of stations sampled (~85%) demonstrated an

excess R_{cint} over GPP_{int} (Goebel et al., In Prep.). These measurements span central and western LIS and the majority of the annual cycle, though they under sample the important winter-spring period. A sound-wide balance demonstrated a similar conclusion. Hence the excess of R_{cint} over GPP_{int} over nearly all sampled stations and dates clearly challenges the conventional assumption that LIS heterotrophic demand is driven by autochthonous carbon production. This observation suggests that previous assumptions of a predominantly autochthonous-driven system during summer, must also be driven by other source(s) of organic matter and/or oxygen sinks. Without identifying and incorporating such sources and sinks in our ecological-physical model, we cannot accurately model oxygen consumption in LIS.

In conclusion, we have demonstrated a proof of concept in our modeling approach, proposed as a useful alternative to modeling oxygen dynamics in LIS. In our new simplified modeling approach we successfully utilized semi-empirical relationships to replace numerous, unknown parameterized processes. The accuracy of the model thus far was demonstrated through corroborations of model outputs and observed measurements of phytoplankton stocks and production, however inconsistency between model outputs and oxygen consumption in LIS may be attributed to a missing carbon source and/or oxygen sink in our model that accurately represents the LIS system. Incorporation of these missing sources and/or sinks into our ecological-physical LIS model could lead to a simpler, more accurate and practical model for strategizing management of hypoxia in LIS.

4. **Project Period:** 1 September 2004 to 31 August 2005

5. **Project Description**

Understanding keystone processes that influence the oxygen dynamics, i.e. primary production and community respiration, of the Long Island Sound (LIS) ecosystem is critical for the investigation and management of hypoxic and anoxic events observed in such eutrophic systems. The uptake of high nitrogen loads by phytoplankton in LIS are thought to drive high rates of primary production, particularly during summer periods of increased light intensities and stratification of the water column. Resultant increases in phytoplankton stocks promote both grazing rates and export of organic matter to the benthos. Increased availability of organic matter stimulates oxygen-consuming heterotrophic processes throughout the water column and at the benthos. Oxygen decrease in bottom waters is exacerbated by increased stratification of the water column, which prevents replenishment of bottom water oxygen concentrations, leading to hypoxia and possibly anoxia. Predictions of "if" and "how much" of a reduction in nitrogen load is necessary to alleviate hypoxic events calls for both a solid understanding of how the system works and the development of a practical tool upon which to base managerial decisions for reduction in nitrogen inputs.

Marked similarities in the along-sound gradients in measurements of primary production (Goebel et al. 2006), the frequency of hypoxia in the bottom waters (CT-DEP), and external loads and internal concentrations of nitrogen (NY-DEC & CT-DEP 2000) of Long Island Sound (LIS) support the idea that nitrogen driven increases in primary production result in the major source of organic matter that leads to summer hypoxic events in this estuarine system. Comprehensive management plans are currently in place to reduce nitrogen inputs to LIS, with the aim to reduce observed hypoxic events. Such managerial decisions call for an accurate, predictive model of LIS that is practicable for the management of this highly eutrophic, seasonally hypoxic system. Recent attempts to numerically model production in LIS (HydroQual 1996; HydroQual 1999) however, provide examples of complex, uncorroborated models that require tuning of a high number of parameters in order to obtain the desired output. Furthermore, support for these models relies on predictions of stocks (e.g. phytoplankton biomass) without confirmation of the underlying rates critical for an accurate, predictive model of processes (e.g primary production) that lead to reduced bottom water oxygen concentrations.

We propose an alternative approach to the complex, highly parameterized models currently used to assess the reduction in nitrogen loads necessary to alleviate hypoxia in LIS. We simplify the model by reducing the number of state variables and parameters necessary to adequately describe the system, and then constrain the values and numbers of free parameters with the use of consistent semi-empirical relationships to model the keystone processes thought to influence oxygen dynamics in LIS. Reduction in the complexity of our modeling approach allows for improved investigation and understanding of the complex relationship between oxygen production and consumption processes and low oxygen concentrations in LIS, that is often masked by a high number of poorly-constrained parameters. Furthermore, such a simplistic model could also bolster its utility as a management tool for evaluating present efforts to reduce nitrogen loads, hence hypoxia, in LIS.

This research has built upon the output of a previously EPA-funded study of Long Island Sound (LIS) "Water Column and Oxygen Production and Consumption: Measurement and Modeling (EPA Cooperative Agreement X-98164401)". In the previous study, a comprehensive set of measured rates of oxygen production and consumption throughout central and western LIS on 15 cruises during 2002 and 2003 enabled (1) characterization of temporal and spatial variations in primary production and community respiration and relationships to phytoplankton stocks and physico-chemical environmental variables (Goebel & Kremer In Press), and (2) annual measurements of primary production and the formulation of a primary production model specific to LIS (Goebel et al. 2006). This sub-model for primary production was then incorporated in a time varying (0-dimensional) ecological model that also included export from the photic zone (upper layer) to the aphotic zone and benthos (lower layer), heterotrophic consumption in the water column and benthos, and benthic remineralization.

The primary objectives of the presently funded study were to (1) implement this 0-d, two-layer ecological model in a 1-d vertically structured water column that varies with time, (2) refine, improve and test the consistency of this 1-d physical-ecosystem model, (3) assess the coupled model in a comparison of model output to measured concentrations of phytoplankton biomass (as chlorophyll), and rates of oxygen production (i.e. primary production) and consumption (i.e. respiration) in LIS, (4) utilize the model to address management issues of hypoxia in the bottom waters of Long Island Sound by exploring the connection of nitrogen source loading with hypoxic events.

We believe that the complex relationship between nutrient loading and seasonal low oxygen conditions in western Long Island Sound requires simple or well-constrained ecosystem models, and ideally both. While doing an acceptable job in achieving observed stocks, previous LIS ecological/oxygen model are neither simple, nor well-constrained. As a result, we have developed and explored a relatively new modeling approach that satisfies both of these criteria, as demonstrated in a schematic diagram of our model (Fig. 1). We hypothesized that LIS oxygen concentration is primarily influenced by advection, diffusion, and fluxes in and from the surface waters and at the bottom benthic layer. This novel ecological model is conceptually quite simple. It includes 4 state variables, 17 parameters most of which are constrained by robust empirical relationships of published cross-system studies and are not free to vary. At the heart of the ecological model is a robust semi-empirical description of primary production in LIS, referred to as the BZI model. Also included is a semi-empirical model for oxygen consumption, driven by autocthonous-driven carbon loads, refered to as the Borsuk model.

The robust, general semi-empirical relationships in our model are used to constrain the value and number of free model parameters. We test the consistency of well constrained, semi-empirical relationships to model the two keystone biological processes thought to contribute to hypoxic events that occur in the bottom waters of LIS during stratified summer periods: the BZI model formulation for primary productivity (Cole & Cloern 1982; Goebel et. al. 2006) and the Borsuk model, originally formulated by Borsuk et al. (2001) to model sediment oxygen demand, and modified to also model oxygen demand within the water column. The Borsuk et al. (2001) empirical approach to model oxygen consumption within the water column was consistent with that of the primary production model, hence was well-suited to our modeling concept. The consistency of

model outputs of primary production and oxygen demand in the water column to that observed in the field were tested in a comparison of computed and field-observed annual rates of primary production and oxygen consumption in LIS. We also explored the connection between nitrogen source loading and hypoxic events produced by the numerical model, in order to address management issues of hypoxia in LIS bottom waters. The refinement, exploration, and corroboration of our ecosystem-physical model for LIS has lead to new and exciting insights into the autotrophic-heterotrophic balance of the LIS system.
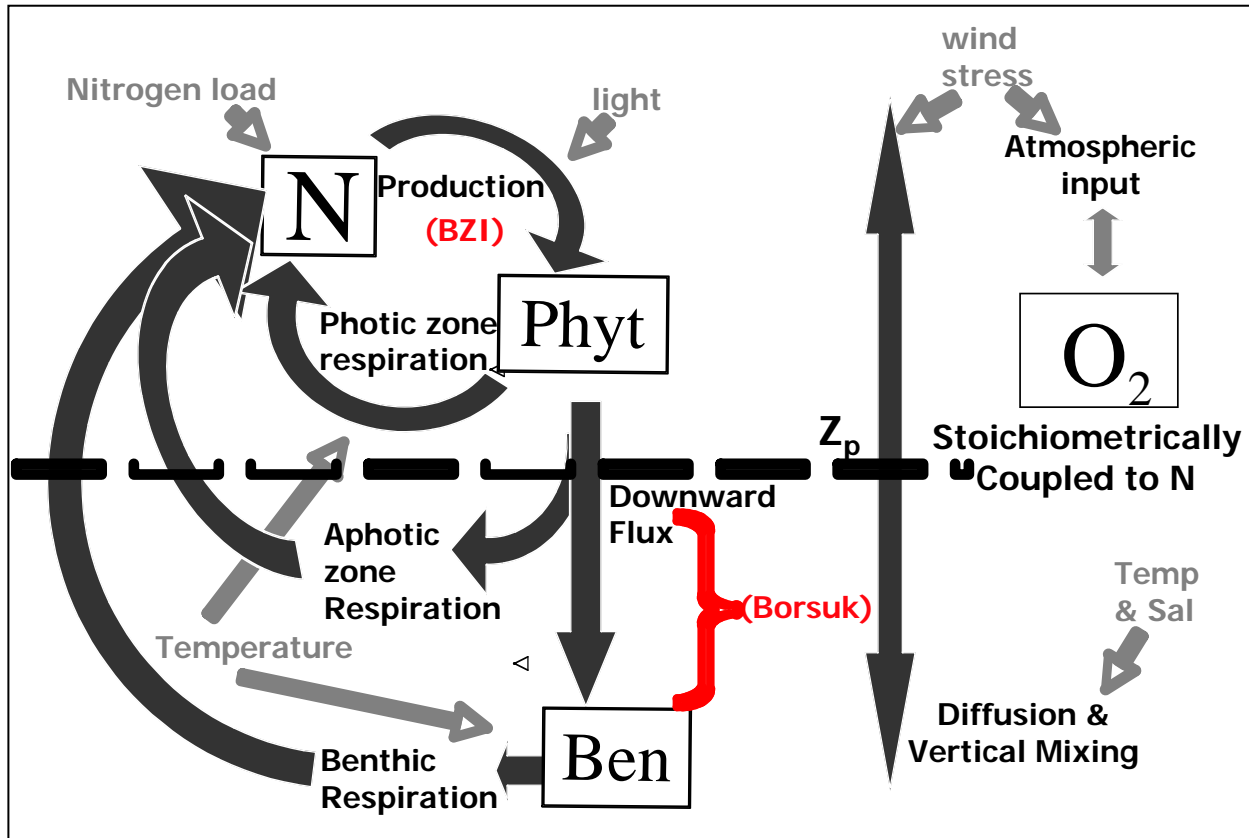
Figure 1. Conceptual model of the proposed 1-dimensional, vertically structured, time-varying ecological-physical model for LIS. State variables Nitrogen (N), Phytoplankton (Phyt), Benthic organic matter (Ben), and oxygen (O2) are in boxes. External inputs, e.g. nitrogen load, light, wind stress, temperature and salinity, are written in grey text. Semi-empirical formulations (BZI and Borsuk) are written in red text. Rate processes (primary productivity, respiration) are written in black text. An external nitrogen load is taken up by phytoplankton via light driven rates of primary production, as modeled with the BZI formulation. Photic zone respiration is driven by remineralization processes, including grazing, represented by an aggregated process that is responsible for the reduction in phytoplankton stocks and remineralization of this organic matter to nitrogen, modeled as a function of a moving average of phytoplankton stocks (as chlorophyll). Phytoplankton is sent to the aphotic portion of the water column using the Borsuk formulation, where this primary source of organic matter is either remineralized within the water column (aphotic zone respiration) or accumulates in the benthos and is remineralized back into nitrogen (benthic respiration). Oxygen, forced by atmospheric inputs of wind and temperature, is a state variable that is stoichiometrically consistent with nitrogen, e.g. remineralization of nitrogen corresponds to an oxygen demand, while the incorporation of nitrogen into phytoplankton biomass corresponds to oxygen production. The physical component of the model includes diffusion, vertical mixing and water column stratification, driven by actual measurements of wind stress and variations in the temperature and salinity structure of the water column.
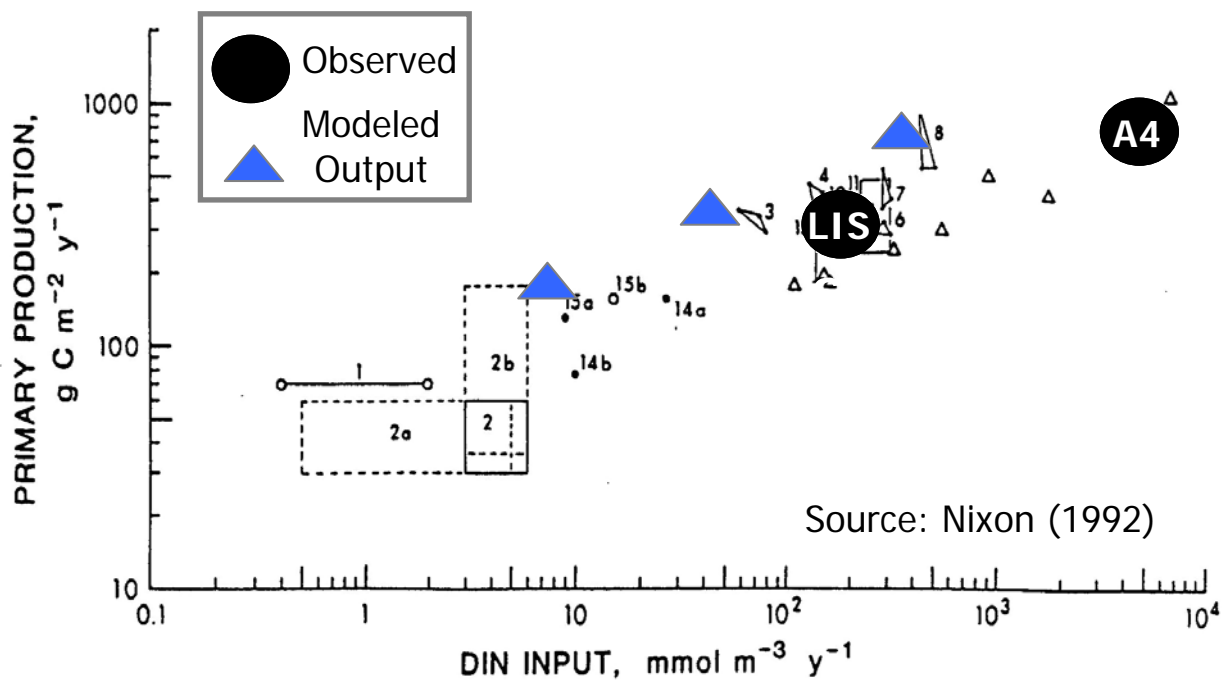
In our ecosystem model of oxygen dynamics in LIS, we use well-constrained, semi-empirical relationships to model the keystone processes that produce and consume oxygen. The consistency of our model is tested by comparing model outputs with the literature, as well as our own measurements and observations of phytoplankton stocks and rates of primary production and water column respiration.
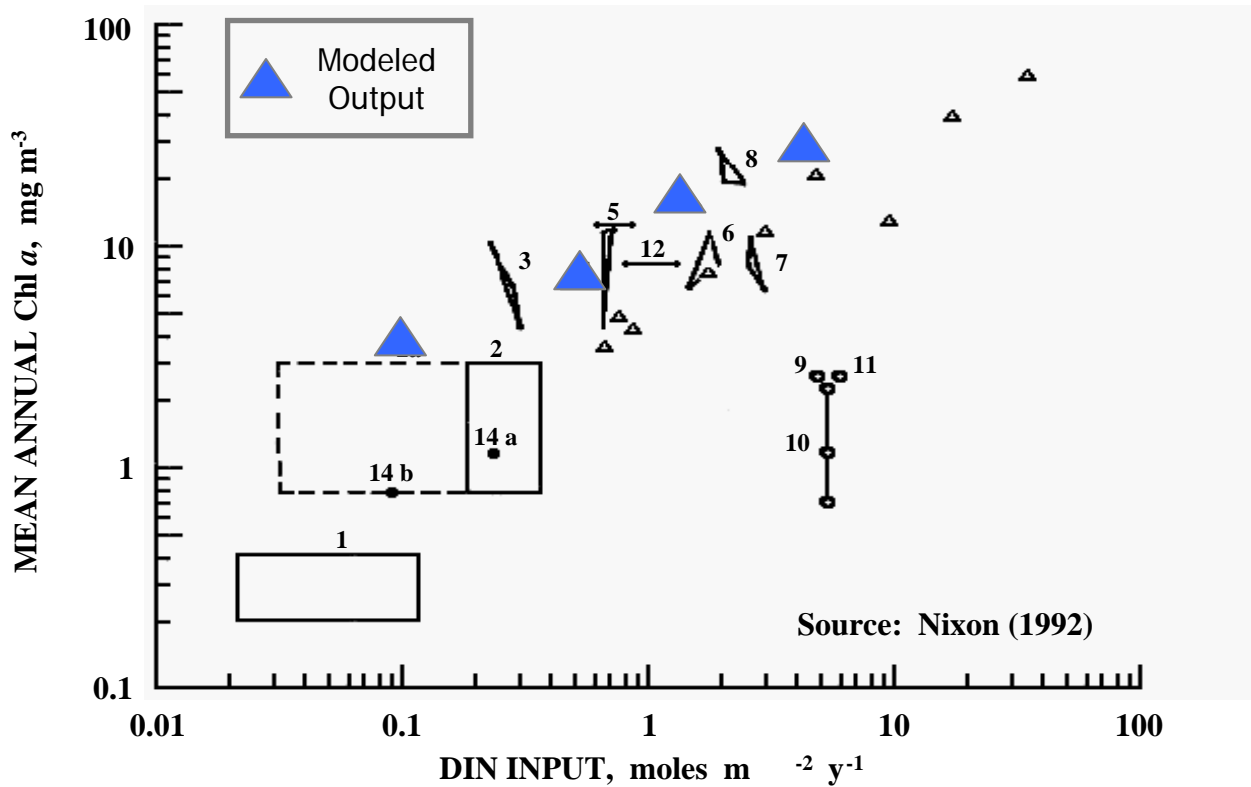
Fig. 2 Agreement between modeled outputs of mean annual phytoplankton stocks, as chlorophyll a, across a range of nitrogen imposed nitrogen loads in LIS, and other estuarine systems investigated by Nixon (1992).

Nixon (1992) reports general trends across a wide range of marine systems in which phytoplankton stocks (as chlorophyll) and rates of primary production vary consistently with total nitrogen inputs. In a series of LIS model runs that impose an increase in external loads of nitrogen inputs, we demonstrate that modeled outputs of annual means of phytoplankton stocks (as chlorophyll) and productivity are consistent with the relationship demonstrated by Nixon across a number of systems (Figs. 2 & 3). We also demonstrate good agreement among measured rates of primary production in LIS as an average for central and western LIS and for the westernmost station of LIS (Fig. 3), demonstrating consistency between our actual measurements and modeled outputs. This cross-system comparison of Nixon's (1992) is independent of the BZI formulation, therefore serves as an independent corroboration of the accuracy of the BZI formulation for primary production in our model.

The Borsuk et al. (2001) semi-empirical formulation for the average annual deposition of organic matter to the benthos, which is converted/equivalent to an annual oxygen demand, is based on information of annual carbon loads, depths, and sediment oxygen demand across 34 estuarine systems, including systems that were included in the former Nixon plots. This semi-empirical relationship uses three parameters, that vary by less than 10%, disallowing for tuning of this robust formulation for oxygen demand as a function of carbon loading, which is assumed to come from autochthonous, primary production for our LIS ecosystem model. Using what information this formulation gives us, we are also able to infer the amount of oxygen demand in the aphotic portion of the water column: Borsuk gives us information about the fraction of autochthonous organic matter, assumed to come primarily from surface production, that is sent to the bottom, and how much production leaves the surface, and the curvature of the relationship and the difference between production that leaves the surface and that which settles on the bottom allows us to calculate the amount of organic matter, hence respiration, that occurs within the aphotic portion of the water column. Within the water column, organic matter is converted directly to oxygen demand. At the sediment layer, organic matter is allowed to accumulate and is further remineralized by benthic processes. This tenuous modification of the Borsuk et al. (2001) model requires a test of consistency to our observed measurements of water column respiration in LIS.

Fig. 3. Agreement between modeled and observed rates of primary production across a range of nitrogen loads for LIS, and other estuarine systems (Nixon 1992).

Comparison of modeled outputs to the field observations of water column respiration are demonstrated using modeled output of daily rates of respiration in the aphotic portion of the water column for a series of model runs, where the few poorly-constrained parameters (4 out of 17) in our model were varied randomly giving us an envelope of possible ranges in oxygen demand associated with inputs of production. When we compare this to measurements that we made in LIS, we get inconsistency in the model with our own measurements made in LIS, where our measurements in LIS are 2-10 times that produced by the model (Fig. 4).
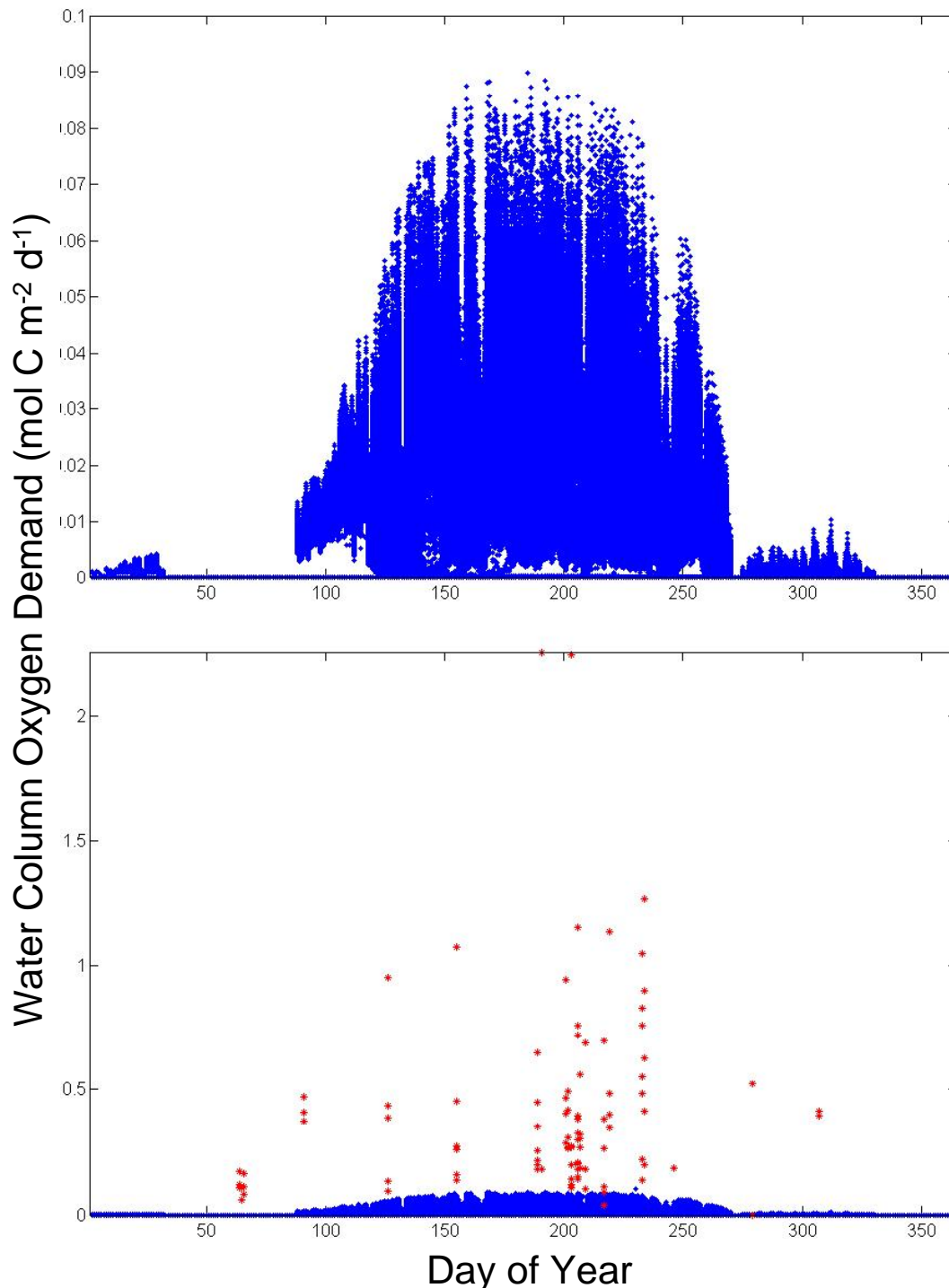
Fig.4. Modeled outputs of daily rates of oxygen consumption in the aphotic portion of the water column (upper plot) versus measured rates of community respiration observed in LIS (lower plot).

This disagreement with modeled outputs and observations lead us to an investigation of where the discrepancy exists – the observed data, the model, or the inconsistency of the Borsuk et al. (2001) model with that of our observed measurements. Several checks ensured that the measured rates of community respiration in LIS (Goebel and Kremer, Unpubl.) were reasonable. 1. The range of measured respiration rates with depth matched very closely the range reported for LIS by Welsh and Eller (1991). 2. Observed average community respiration in LIS (~30 mmol C m^{-3} d^{-1}) was higher than, but well within the range of, the average calculated

in a cross-system literature review of 21 estuaries (~18 mmol C m^{-3} d^{-1}; Hopkinson and Smith, 2004).
3. Estimates of bacterial respiration (0.3 to 1.5 mmol O_2 m^{-3} h^{-1}; McManus, pers. comm.) based on actual profiles of bacterial counts in LIS, assuming a growth rate of 1 d^{-1} and growth efficiency of 10-50%, were also consistent with the range of community respiration measurements in LIS (0.3 to 1.9 mmol O_2 m^{-3} h^{-1}; Goebel and Kremer, In Press). This indicates that our measurements are not only reasonable, but also representative of the microbial community specific to the LIS ecosystem. 4. Lastly, measurements of dissolved organic carbon (DOC) measured in LIS are shown to be an ample source of organic matter (1.5 to 2 g C m^{-3}; Vlahos, pers. comm.), sufficient to support 5-40% of our observed daily rates of community respiration, suggesting that the fuel necessary to drive our observed community respiration is readily available. Hence we felt confident that our comprehensive set of community respiration observations, as well as our detailed calculations of GPP (Goebel et al., 2006), in LIS are reasonable and representative of this highly productive system.

In a comparison of measured rates integrated over the depth of the water column of community respiration (R_{cint}) and gross primary production (GPP_{int}), the majority of stations sampled (~85%) demonstrated an excess R_{cint} over GPP_{int} (Goebel et al., In Prep.), usually by 2 to 6 times. These measurements span central and western LIS and the majority of the annual cycle, though they under sample the important winter-spring period. A sound-wide balance demonstrated a similar imbalance. Temporal variation in this ratio demonstrates that this ratio is highest when high summer productivity decreases during other times of the year. Spatially, there was no evidence for a strong gradient in the ratio of R_{cint}:GPP_{int}, which may be explained by the presence of strong gradients in both of these rates along the length of the sound. Hence the excess of R_{cint} over GPP_{int} over nearly all sampled stations and dates clearly challenges the conventional assumption that LIS heterotrophic demand is driven by autochthonous carbon production. Assuming that our measurements are accurate and represent the LIS ecosystem, this observation suggests that previous assumptions of a predominantly autochthonous-driven system during summer, must also be driven by other source(s) of organic matter and or oxygen sinks.

In conclusion, we have demonstrated that our new simplified modeling approach can successfully utilize semi-empirical relationships to replace numerous, unknown parameterized processes has demonstrated to be a useful alternative to modeling oxygen dynamics in LIS. We also demonstrated the accuracy of our model thus far through corroborations model and observed measurements of phytoplankton stocks and production, but found that although the Borsuk model did not produce results that agreed with our data. This inconsistency between model outputs and oxygen consumption in LIS may be attributed to a missing carbon source and/or oxygen sink in our model. Identification of such processes that drive the high rates of oxygen consumption observed in LIS can then be incorporated into the existing model, to improve predictions of oxygen consumption, hence hypoxia, in LIS.

To date we are able to show that our modeled annual averages of productivity and chlorophyll stocks agree with observations in LIS, as well as the relationship between nitrogen loads and primary production in other systems. The next step is to demonstrate that our model is able to simulate temporal variations in production and chlorophyll observed in LIS. It is also important for the model to be able to capture the timing of hypoxia and anoxic conditions in LIS. Agreement between these model outputs and observations will enable us to use this 1-dimensional, time-varying ecological model to improve our understanding of oxygen dynamics and hypoxia in LIS, in order to bolster its utility as a management tool for evaluating present efforts to reduce nitrogen loads to LIS.

6. **Activities & Accomplishments:**

We have successfully coupled our ecological model to a simplified form of the physical model, to form a time varying, vertically structured (1-d) ecological-physical model consistent with the parent 3-d hydrodynamic model of LIS. This has provided an ideal testing ground for the physical-biological structure of the model

(Fig. 1). The physical submodel incorporates sinking of phytoplankton and detritus, and turbulent diffusion of compartments representing phytoplankton, zooplankton, detritus, nitrogen, and oxygen into the model. The ecological model contains four submodels: 1) a primary production formulation corroborated for LIS (EPA award X-98164401; Goebel and Kremer, in press), 2) heterotrophic consumption in the water column and the benthos, 3) export from the photic zone to the benthos and 4) benthic remineralization and denitrification. The submodels initially proposed for (3) and (4) have been dramatically modified. Export of phytoplankton and benthic remineralization is currently being modeled with the use of a semi-empirical model formulated for sediment oxygen demand (SOD) by Borsuk et al. (2001). In this formulation, SOD is driven by the deposition of particulate production from the photic zone using a statistical relationship between measured inputs of organic matter and SOD across 34 estuarine and coastal systems of varying organic inputs and water depths, fit and parameterized to an empirical model. The Borsuk model reduces the complexity of the ecological model, and it is based on a wide selection of site-specific data which confers the important generality to this approach. This formulation, as successfully compared to the more traditional approach to modeling export and remineralization (see previously funded research), serves as a useful tool for investigating the processes that lead to hypoxic conditions in LIS.

Corroboration of our model with field observations of primary production and water column respiration confirmed the applicability of the BZI formulation in predicting primary production in LIS, however the disagreement of the output of the Borsuk et al. (2001) model for oxygen demand and our field observations have lead to new insights into the balance between heterotrophic and autotrophic processes in LIS.

Difficulties in obtaining SWEM model outputs from Hydroqual resulted in the inability to obtain one of our objectives, which was to compare our model output with that of the existing LISS/SWEM model, and we were thus unable to evaluate the adequacy of the alternative formulations.

7. **Modeling:**

    A. Model description, key assumptions, version, source and intended use:

The ecological processes within our 1-dimensional, vertically structured, time-varying model are essentially divided into photic and aphotic zones (Fig. 1 & Table 2). Primary production (PP) occurs exclusively within the photic zone, calculated using the semi-empirical BZI formulation of Cole & Cloern (1987). In the photic zone, an aggregate heterotrophic process, referred to as photic zone heterotrophic respiration, is responsible for decrease in phytoplankton stocks and remineralization of this organic matter to nitrogen. Detrital organic matter, assumed to originate solely from primary production, is transferred from the upper mixed layer to the lower mixed layer, using a semi-empirical function formulated by Borsuk et al. (2001). This portion of the accumulation of organic matter at the benthic layer is remineralized back into nitrogen via a temperature-dependent function of organic matter that is sent to the sediment by the Borsuk formulation. Denitrification is accounted for by designating a portion of the productivity sent to the benthos by the Borsuk formulation to be lost to unbiologically available nitrogen gas. The ecological model is coupled to a vertically structured physical model that is based on a simplification of the formulation of (Large, McWilliams et al. 1994), driven by actual records of wind velocity, and profiles of temperature and salinity, to calculate diffusion, vertical mixing, and stratification of the water column.

Our simple modeling approach reduces the number of model components to 4 state variables (Nitrogen (N), Phytoplankton (Phyt), Benthic organic matter (Ben), Oxygen (O)) and 17 variable parameters (Table 1). Of the 17 necessary ecological parameters, one is fixed within the BZI model, three within the Borsuk model, and 7 are necessary for describing other biological (heterotrophic processes in the water column and the

benthos) and physical (light attenuation properties and eddy diffusivity) processes. The model is driven by actual variations in incident irradiance (I_o) and wind velocity (quarter-hourly), external inputs of nitrogen (monthly), and water column profiles of temperature and salinity (monthly).

Table 1. Definitions and values of assigned parameters in our ecological model.

Parameter	Description	Value	units	constrained
BZI_slope	BZI model constant	0.8	m µmol photons^{-1}	well
Borsuk_a	Borsuk model constant	0.76	-	well
Borsuk_b	Borsuk model constant	0.79	-	well
Borsuk_k	Borsuk model constant	0.0008	-	well
PQ	Photosynthetic quotient	1.2	mol O_2 mol CO_2^{-1}	well
RQ	Respiratory quotient	0.9	mol CO_2 mol O_2^{-1}	well
CChl	Carbon to chlorophyll ratio	40	mg C mg Chl^{-1}	well
- PnLc	Converts productivity units of mg Chl m^{-2} s^{-1} to mol C m^{-2} y^{-1}	105120	mol C s mg Chl^{-1} y^{-1}	-
- SODChl	Converts productivity units of mol C m^{-2} y^{-1} to mg Chl m^{-2} s^{-1}	9.51e^{-06}	mg Chl y mol C^{-1} s^{-1}	-
- NChl	Converts units of nitrogen (µM) to units of chlorophyll (µg L^{-1})	0.5031	ug Chl µmol N^{-1}	-
- OChl	Converts units of oxygen (mg L^{-1}) to units of chlorophyll (µg L^{-1})	0.1067	ug Chl mg O_2^{-1}	-
Ks	Half-saturation constant for phytoplankton uptake of nitrogen	1	µM	well
Denitr_loss	Denitrification constant	0.3	%	well
PPr0	Phytoplankton respiration at T=0 C	0.01	d^{-1}	poorly
PPr0_Q10	Q_{10} for phytoplankton respiration	0.07	C^l	well
Rf0	Photic zone heterotrophic processes at T=0 C	0.06	d^{-1}	poorly
Rf0_Q10	Q_{10} for photic zone heterotrophic processes	0.07	C^{-1}	well
Rb0	Sediment heterotrophic respiration at T=0 C	0.12	d^{-1}	poorly
Rb0_Q10	Q_{10} for sediment heterotrophic respiration	0.07	C^{-1}	well
λ	Ivlev constant	0.4	m^3 mg Chl^{-1}	well
TimePbar	Time averaged to calculate photic zone heterotrophy	10	d	poorly

ECOLOGICAL MODEL

The semi-empirical formulations for oxygen production in the photic zone and oxygen consumption in the aphotic portion of the water column are coupled to the following simplified, aggregate processes for grazing, nutrient remineralization and oxygen consumption in the photic zone, and sediment microbial processes responsible for oxygen consumption and reallocation of remineralized nitrogen.

Photic Zone Heterotrophic Processes (PH): This aggregate process assumes the role of grazing, nutrient (nitrogen) remineralization, and oxygen demand in the photic zone. PH is closely coupled to phytoplankton stocks and rapidly recycles nutrients from algal biomass to biologically available form while consuming the stoichiometric proportion of oxygen. This is demonstrated by the equation in Table 2, where PH is a temperature-dependent function of the 10-day moving average of phytoplankton stocks (as chlorophyll). An

Ivlev function is utilized to ensure that no reduction in phytoplankton stocks occurs when phytoplankton stocks are already depleted.

Sediment Oxygen Demand (SOD): Detrital organic matter that is sent to and accumulates at the benthic layer via the Borsuk formulation (see above) is remineralized to nitrogen as a temperature-dependent function of the pooled organic matter at the sediment-water interface (Table 2). A stoichiometric proportion of oxygen is consumed in the bottom-most layer of the water column during this process.

Sediment Denitrification (SDn): The denitrification process in the sediment layer has been reported to account for the removal of 30% of nitrogen flux to the water column. We incorporate this loss of nitrogen into our ecological model by increasing the amount of organic matter lost to this microbial process by 30% (Table 2). This is a rough estimate based on general relationships of N retention and denitrification with basin residence time (Nixon, Ammerman et al. 1996).

The complete ecological model (Fig. 1) is then coupled to a 1-dimensional, vertically-structured hydrographic model. Accuracy of the well-constrained formulations of keystone biological processes, as well as output of state variables/stocks, are tested through comparison of model outputs with field observations.

PHYSICAL MODELS

Hydrographic Model:
The hydrographic model is configured as a 1-dimensional (vertical) water column, extending from the surface to 30 meters depth and resolved into 1 meter bins. Although this simple approach neglects horizontal transports, it does allow vertical mixing (diffusion) of all state variables, which we believe is one critical process over the annual cycle. Vertical mixing is based on a modified version of the KPP formulation (Large et al. 1994). The mixed layer depth is determined from a bulk Richardson number criterion, with an assumed profile of horizontal velocity (i.e., prescribed vertical shear, based on a known tidal velocity scale). The magnitude of the mixing coefficient within the mixed layer scales as the product of the mixed layer depth and a turbulent velocity scale. Within the mixed layer, the mixing profile varies as a cubic polynomical with depth and matches smoothly to a constant background level at the mixed layer base. Time-stepping is split, with the biological processes integrated using an explicit 4th order Runge-Kutta algorithm with implicit diffusion determined using a 2nd order Crank-Nicholson scheme. Our model uses measured quantities where possible. The temperature and salinity structure is interpolated from profiles as part of this project, and wind velocities (measured at Millstone Environmental Laboratory) are applied to influence the time-dependent turbulent velocity scale. As a result, a relatively realistic annual cycle of mixed layer depth results, with seasonal mixed layer as shallow as 3 m developing in springtime and lasting until fall storms erode the stratification and completely overturn the water column.

Atmospheric Oxygen Flux:
Atmospheric exchange is calculated from the saturation deficit between the oxygen concentration in the surface layer and the concentration at equilibrium with the atmosphere, based on temperature and salinity. A gas exchange coefficient (expressed as "piston velocity", KL) yields the area exchange rate D (g O_2 m^{-2} d^{-1}). For these initial runs, KL was was determined as a function of wind speed at 10m elevation (U10, m/s) (Kremer, Reischauer et al. 2003).

```
------------------
KL=param(29);
…
%%Calculation of oxygen concentration in surface layer at
%%equilibrium with atmosphere (therefore average of daily variation)
SatOx=14.161-.3942*T+7.714e-3*T^2-6.46e-5*T^3-S*(.0841-.00256*T+3.7e-5*T^2);
SDef=SatOx-Os;   %mg O/L = gO/m3
D=KL*SDef;      %g O/m2/d - Diffusion piston velocity
…
dOsdt = (PnChl-grz)*CHLO2 + D/Zs + DzO/Zs;          %(mg O2/L/d), D=diffusive flux (gas exchange)
------------------
```

Horizontal transport
The 1-d structure of the model does not currently incorporate horizontal transport.

Model Kludge
In order to avoid negative stocks of state variables, we include backup solutions for situations where numerical methods overshoot reductions in state variables. No phytoplankton growth occurs if there is not enough nitrogen to support growth over the subsequent time step. There is a shift in resources when stocks go negative. Such artificial fixes are kept track of in a budget, and do not occur regularly/often.

The intended use of the ecological-physical model is to evaluate sources and fate of summer production of pelagic organic matter and its contribution to bottom hypoxia, thus helping to improve our understanding of the processes that contribute to hypoxia in LIS and evaluate management strategies to reduce nitrogen inputs.

   b.   Performance criteria and assessment for the model related to the intended use, and

A key question is the usefulness of the alternative formulation approach being employed in the ecological-physical model. Model performance criteria and testing of the model performance are primarily assessed by the comparison of modeled output with field data collected by the CT-DEP monitoring surveys and published relationships demonstrating the link between nitrogen loads and oxygen production and consumption (Fig. 3 & 4). Specifically, model outputs of varying versions of the physical model are compared to observed rates of primary productivity (Fig. 3) and plankton respiration (Fig. 4), and phytoplankton standing stock (Fig. 2). The ability of the model to predict rates of primary production and planktonic respiration is imperative, since these are the keystone processes which are most important to model accurately in order to investigate the effects of nitrogen loads on hypoxia.

Our emphasis for model validation is on the prediction rate processes affecting oxygen production (autotrophy) and consumption (heterotrophy). Agreement between model outputs of primary production and community respiration across a range of imposed nitrogen loads that correspond to the observed gradient in nitrogen loads in LIS, enables demonstration of the proof of concept of our modeling approach that uses alternative formulations to predict key processes that affect oxygen concentrations in LIS. Furthermore, agreement between these model outputs and published relationships in the literature that demonstrate the link between nitrogen inputs and rates of phytoplankton production and phytoplankton stocks, demonstrate the wide applicability of the model and is an independent corroboration of the validity of the formulated ecological-physical model.

This approach is used to assess our modeled versus our observed data, and a similar strategy could be used to assess our model versus other model predictions, such as those of SWEM. The model will not be accepted or rejected based on any pre-determined numerical criteria, however. In the present and the concurrent study we are exploring the general accuracy of new formulations, and our goal is to characterize the potential and relative usefulness of the approach. Direct rigorous validation may not be possible and is not a goal. Initially, the physical model will not attempt to simulate a specific period of time in LIS. Thus a careful comparison of stocks from a specific field study cannot be conclusive. While we may be able to run our physical model for similar meteorological (i.e. irradiance, temperature) conditions in the Sound, substantial or at least unknown differences in the modeled physical conditions will persist. For these reasons, our assessment in this initial phase of the development and evaluation of our model will focus on general agreement for the physiological formulation of net primary production and respiration rates, as described above.

c.   Test results to demonstrate the model performance criteria were met

In our ecosystem model of oxygen dynamics in LIS, we use well-constrained, semi-empirical relationships to model the keystone processes that produce and consume oxygen. The consistency of our model is tested by comparing model outputs with the literature, as well as our own measurements and observations of phytoplankton stocks and rates of primary production and water column respiration.

Nixon (1992) reports general trends across a wide range of marine systems in which phytoplankton stocks (as chlorophyll) and rates of primary production vary consistently with total nitrogen inputs. In a series of LIS model runs that impose an increase in external loads of nitrogen inputs, we demonstrate that modeled outputs of annual means of phytoplankton stocks (as chlorophyll) and productivity are consistent with the relationship demonstrated by Nixon across a number of systems (Figs. 2 & 3). We also demonstrate good agreement among measured rates of primary production in LIS as an average for central and western LIS and for the westernmost station of LIS (Fig. 3), demonstrating consistency between our actual measurements and modeled outputs. This cross-system comparison of Nixon's (1992) is independent of the BZI formulation, therefore serves as an independent corroboration of the accuracy of the BZI formulation for primary production in our model .

The Borsuk et al. (2001) semi-empirical formulation for the average annual deposition of organic matter to the benthos, which is converted/equivalent to an annual oxygen demand, is based on information of annual carbon loads, depths, and sediment oxygen demand across 34 estuarine systems, including systems that were included in the former Nixon plots. This semi-empirical relationship uses three parameters, that vary by less than 10%, disallowing for tuning of this robust formulation for oxygen demand as a function of carbon loading, which is assumed to come from autochthonous, primary production for our LIS ecosystem model. Using what information this formulation gives us, we are also able to infer the amount of oxygen demand in the aphotic portion of the water column: Borsuk gives us information about the fraction of autochthonous organic matter, assumed to come primarily from surface production, that is sent to the bottom, and how much production leaves the surface, and the curvature of the relationship and the difference between production that leaves the surface and that which settles on the bottom allows us to calculate the amount of organic matter, hence respiration, that occurs within the aphotic portion of the water column. Within the water column, organic matter is converted directly to oxygen demand. At the sediment layer, organic matter is allowed to accumulate and is further remineralized by benthic processes. This tenuous modification of the Borsuk et al. (2001) model requires a test of consistency to our observed measurements of water column respiration in LIS.

Comparison of modeled outputs to the field observations of water column respiration are demonstrated using modeled output of daily rates of respiration in the aphotic portion of the water column for a series of model runs, where the few poorly-constrained parameters (4 out of 17) in our model were varied randomly giving us an envelope of possible ranges in oxygen demand associated with inputs of production. When we compare

this to measurements that we made in LIS, we get inconsistency in the model with our own measurements made in LIS, where our measurements in LIS are 2-10 times that produced by the model (Fig. 4).

     d.   Theory behind the model, expressed in non-mathematical terms;

Over-parameterization and limited data to check the consistency of the model reduce both understanding and accuracy of the model outputs. We propose here an alternative modeling approach that constrains the value and number of parameters necessary to model oxygen dynamics in LIS through the use of robust, general semi-empirical relationships. We test the following formulations for the keystone processes of oxygen production (primary production) and consumption (aphotic zone heterotrophic respiration) that contribute to hypoxic events in the bottom waters of LIS during summer:

Primary Production (PP): Formulating a relationship among site-specific measurements of productivity, and easily, often routinely, measured variables enable the formulation of a valid, practicable model for primary production. A robust, general semi-empirical model for primary production is based on the relationship between daily integrated rates of net production in the photic zone and a composite parameter, BZI, composed of phytoplankton stocks (B), depth of the photic zone (Z), and irradiance levels (I). Corroboration of this sub-model to the waters of central and western LIS (Goebel, Kremer & Edwards, 2006) demonstrates the consistency of this model across numerous systems (Brush et al. 2002).

Sedimentation of Organic Matter and Aphotic Zone Heterotrophic Processes (AH): A similar semi-empirical modeling approach is taken for the export of organic matter and the subsequent oxygen demand associated with remineralization processes in the water column and at the sediment layer. Utilization of this semi-empirical relationship reduces the value and number of unconstrained parameters by avoiding the specification of mortality, sinking and remineralization rates, which commonly range across orders of magnitude. Borsuk et al. (2001) formulated a semi-empirical relationship between carbon loading and water column depth and resultant sediment oxygen demand across 34 estuarine and coastal systems. This relationship is utilized to estimate export of phytoplankton to the water column below the mixed layer or photic zone (whichever is deeper) and the sediment layer. Organic matter sent to the water column follows the premise of the Borsuk model and is immediately remineralized resulting in an oxygen demand. In contrast, organic matter sent to the benthos and allowed to accumulate. This modification of the Borsuk model was required in order to represent a relationship that is formulated over an annual period, to one that is calculated on daily or even hourly time scales. This semi-empirical formulation was taken directly from Borsuk et al. (2001), and not tested directly within LIS. Results of the model, however, demonstrate a relatively tight relationship across a large number of estuarine types, including data from eutrophic systems (>90%) whose depths are similar (<60 m) to LIS.

The sub-formulations for primary production and aphotic zone heterotrophic respiration are coupled to three other ecological processes representing photic zone and benthic heterotrophic processes (see below) in order to complete the ecological model. Although these heterotrophic processes in the photic zone and benthic layer are not yet modeled utilizing semi-empirical formulations, we continue to constrain the number of parameters through the use of simple, aggregate formulations.

We test the consistency of these well-constrained formulations in a 1-dimensional, vertically structured, time-varying ecological model for rates of primary production and bottom water oxygen levels observed in western and central LIS.

e.   Mathematics to be used, including formulas and calculation methods:

Formulations for primary production (PP), heterotrophic processes in the photic (PZH) and aphotic (AZH) zones, sediment oxygen demand (SOD) and denitrificiation are listed in Table 2.

Table 2. Definitions and formulations for biogeochemical equations used within the ecological

model.

Process	Location	Formulation Type	Formula	# of Parameters
Primary Production (PP)	Photic Zone	BZI	$BZI\_slope*PB*Z_p*Io*(N/(BZI\_Ks+N))$	1 (fixed)
Photic Zone Heterotrophy (PZH)	Photic Zone	Aggregate	$Rf0*exp^{(RfQ10*T)} * Pbar*(1-exp^{(-\lambda_r*PB)})$	2 (not fixed)
Aphotic Zone Heterotrophy (AZH)	Aphotic Zone	Borsuk	$Borsuk\_a*((L_c/(1+ Borsuk\_k*L_c*h))^{Borsuk\_b}$	3 (fixed)
Sediment Oxygen Demand (SOD)	Benthos	Aggregate	$Rb0*exp^{(RbQ10*T)} * BB$	2 (not fixed)
Denitrification (SDn)	Benthos	?	$(Denitr\_loss \; \check{S} \; 1) * Borsuk\_a*((L_c/(1+ Borsuk\_k*L_c*h_{ml/Zp}))^{Borsuk\_b}$	1 (fixed)

An indicator for the presence of anoxic conditions was implemented to conserve anoxic conditions and prevent heterotrophic remineralization of nitrogen under anoxic conditions using the following piece of code:

```
if anox==1
   ben=ben + bot;
   bot=0;
   if Ob <= 0
      SD = 0  ;        % If Ob < 0 don't allow any SD.
   else
      SD=Ob*Zb/CHLO2;
      if SD>SDx
         SD=SDx
      end
   end
end
```

A fourth-order Runge-Kutta integration scheme (see code in appendix) is used to approximate the derived state variables at each time step. The formulas for the derivatives of each state variable are as follows:

Phytoplankton
```
dPdt(z) = PP(z) - Phytresp(z) – PZH(z) – AZH(z);%
```

Detritus
```
dDdt(z) = PZH(z) – AZH(z) - SDn;
```

Nitrogen
```
dNdt(z) = Next + PZH(z) + AZH(z) + Phytresp(z) – PP(z) + SDn
```

Oxygen
```
   %    add atmospheric forcing
        if (z > 1)
            OAtm(z)=0.0;
```

```matlab
        else
            SatOx = 14.161 ...
                    - (.3942*Temp(z)) ...
                    + 7.714e-3*(Temp(z)*Temp(z)) ...
                    - 6.46e-5*(Temp(z)*Temp(z)*Temp(z)) ...
                    - Salinity(z)*(.0841-(.00256*Temp(z))+3.7e-5*(Temp(z)*Temp(Z))
%       mg O/L = gO/m3
            SDef=SatOx-O(z);
%       g O/(m^2 s) - Diffusion piston velocity
            hght_v = 67/33 ; % ratio of known:desired windspeed height
            u10 = windspeed.*hght_v.^-.12; %conversion
            %of wind speed at hght_v to equivalent at 10m....
            BZI_KL = 3.0*(exp(0.25*(u10)))*24/(100*SECPERDAY); %windspeed=m/s.
                                %KL in cm/hr*24/SECPERDAY/100= m/s.
            OAtm(z)=BZI_KL*SDef.*(dzF(z).*hFacC(z)); %m/s*mgDO/m3*1/m=mgDO/m2 s
dOdt(z) = OAtm(z) + PP(z) - Phytresp(z) + PZH(z) + AZH(z) - SDn
All state variables ere converted to units/currency of nitrogen concentration.
```


     f.   Whether or not the theory and mathematical algorithms were peer reviewed, and, if so, include a summary of theoretical strengths and weaknesses:

     g.   Number of and uncertainty associated with parameters

     h.   Input data requirements

Theory behind the formulation for primary production, the BZI model, has been tested and applied to other estuarine systems, as published in peer-reviewed journals. The strength of the BZI model formulation for primary productivity is that it is well-constrained, robust, general, and simple to implement (Brush et al 2002). Although the BZI formulation has been demonstrated to apply to a variety of nitrogen-loaded, estuarine systems, it has not been successful in complex systems such as Chesapeake Bay (Harding et al. 2002), where conditions extend beyond the capability of the model. Therefore, the BZI formulation has been tested within the LIS system before being implemented (Goebel et al. 2006).

The number of parameters were minimized, and either corroborated directly to the LIS system (i.e. primary production) or obtained from general, well-established semi-empirical relationships (e.g. oxygen demand (SOD)) in the literature. Minimization of the number of parameters reduces the complexity, thus the uncertainty of the model. Corroboration of rates of primary production measured in LIS to the formulation for primary production in LIS strengthens the validity of these predicted rates within the ecological model. Parameters obtained from well-established semi-empirical relationships in the literature (SOD; Borsuk et al. 2001) are not as robust as direct corroboration of a model formulation to the LIS system, however the generality and simplicity of the Borsuk et al. (2001) model is likely to be an improvement over attempts to improve the model through an increase in a number of parameters (i.e. complexity) that vary more widely across a variety of systems (i.e. uncertainty).

Our simple modeling approach reduces the number of model components to 4 state variables (Nitrogen (N), Phytoplankton (Phyt), Benthic organic matter (Ben), Oxygen (O)) and 17 variable parameters (Table 1). Of the 17 necessary ecological parameters, one is fixed within the BZI model, one within the Borsuk model, and 7 are necessary for describing other biological (heterotrophic processes in the water column and the benthos) and physical (light attenuation properties and eddy diffusivity) processes. The model is driven by actual variations in incident irradiance (I_o) and wind velocity (quarter-hourly), external inputs of nitrogen (monthly), and water column profiles of temperature and salinity (monthly). External nitrogen input is based on documented annual estimated inputs of nitrogen to LIS. Equilibrium of surface water oxygen concentration with the atmosphere is modeled utilizing piston diffusion velocity, based on average wind speeds found in LIS.

Rates of primary production are corroborated to LIS based on the semi-empirical BZI formulation, whose slope of 0.9 varies by 7%. A monod nutrient limitation is applied to phytoplankton growth rates, utilizing a half-saturation coefficient of one. A phytoplankton respiration of 20% of phytoplankton biomass was assumed for the aphotic portion of the surface layer. Heterotrophic processes in the water column and benthos are based on a temperature-dependent relationship, both assigned a Q_{10} of 2 and initial respiration rates at zero temperature of 0.1 and 0.01, respectively. Export of organic matter is based on the semi-empirical model of Borsuk et al. (2001), based on the relationship between the input of organic matter to a system and the amount of benthic sediment oxygen demand. This semi-empirical relationship, based on a model fit to a wide variety of estuarine systems, uses three parameters that vary by less than 10%, disallowing for tuning of this robust formulation for oxygen demand An indicator for the presence of anoxic conditions was implemented to conserve anoxic conditions and prevent heterotrophic remineralization of nitrogen under anoxic conditions (see code in section e. and appendix).

    i.   Hardware requirements:

The model was run using Matlab version 7.0, on a personal computer.

    j.   Documentation (e.g., users' guide, journal publications, model code).

8. Summary of Findings:

A new model for LIS has been implemented by coupling an existing model of ecological response to estuarine nitrogen loading with a numerical hydrodynamic model. This model evaluates sources and fate of summer production of pelagic organic matter and its contribution to bottom water hypoxia in LIS. The design strategy of our ecological model is based on simplicity and generality, to minimize uncertainty due to poorly specified model parameters. Reducing the complexity of the ecosystem component of our ecological-physical model of oxygen dynamics in LIS, by basing critical rate processes on available data is desirable, achievable, and beneficial. Incorporation of measured and corroborated rates of oxygen metabolism using semi-empirical formulations will simplify the development of the model by limiting the number of free parameters that control ecosystem dynamics. It should also simplify model interpretation and increase the accuracy of the predictions, as assessed by the agreement between the output of the model and actual measurements of oxygen production and consumption across a range of nitrogen loads. Modeled and measured phytoplankton productivity and stocks within LIS, as well as a across a number of other systems, over a range in nitrogen loads demonstrated good agreement (Figs. 2 & 3). Modeled and measured rates of oxygen consumption over a wide range in nitrogen loads and the four poorly-constrained parameters in our model however, did not demonstrate good agreement with modeled rates an order of magnitude lower than that observed (Fig. 4). This disagreement in oxygen consumption rates in LIS has lead to further investigations of the imbalance between oxygen production and consumption in LIS, and suggests that there is either an unidentified source of carbon input and/or oxygen sink.

9. **Conclusions:**

This modeling effort addresses the research needs of LIS and surrounding states of CT, NY and RI, by developing a new numerical model that accurately represents changes in the rates of primary production and phytoplankton stocks across a range of imposed nitrogen loads. The primary productivity component of the model is strongly corroborated with site-specific measurements made in LIS (Goebel et al. 2006), as well as across a range of other ecosystems (Nixon 1992), therefore provides a model that can accurately predict phytoplankton production and stocks in the LIS ecosystem, as well as across other ecosystems. We were not however, able to accurately represent oxygen consumption in the water column using the modified version of the Borsuk et al. (2001). This disagreement however, lead to further investigation of the balance between

oxygen production and consumption in LIS, which, based on actual measurements in LIS, indicates that there is an unmeasured source of carbon entering LIS or an unmeasured sink of oxygen (Goebel et al., In Prep.). This poses further questions as to the carbon sources and sinks that influence the LIS system, proposing further studies that shall increase our understanding of the LIS environment. Incorporation of these missing sources and/or sinks into our ecological-physical LIS model could lead to a simpler, more accurate and practical model for strategizing management of hypoxia in LIS.

10. Publications/Presentations:

Manuscripts for Published

Goebel, N.L., J.N. Kremer, C.A. Edwards (2006). Primary Production in Long Island Sound. Estuaries and Coasts. 29(2): 232-245.

Goebel, N.L. and J.N. Kremer (In press). Spatial Variability of Photosynthetic Parameters and Community Respiration in Long Island Sound. Marine Ecological Progress Series.

Manuscripts for Publication

Goebel, N.L., J.N. Kremer, C.A. Edwards. An Alternative Source of Labile Organic Matter for Community Respiration in Long Island Sound. Target submission date: October 2006.

Goebel, N.L., C.A. Edwards, J.N. Kremer. A Biological-Physical Numerical Simulation Model for the Investigation, Prediction, and Management of Oxygen Production and Consumption in Long Island Sound. Target submission date: December 2006.

Conferences & Seminars

Goebel, N. Invited lecturer, USGS (Menlo Park, CA) Seminar Series. 2006. "Measuring and Modeling Keystone Processes that Lead to Hypoxia in Long Island Sound."

Goebel, N., J. Kremer, C. Edwards. 2005. Detailed Calculations of Integrated Primary Production in Central and Western Long Island Sound. ASLO, Salt Lake City UT. Oral presentation by Goebel, publ. Abstract.

Kremer, J. N. 2005. Invited seminar, Australian CSIRO Marine Division: A General Model of Ecological Responses to Nitrogen Loading in Shallow Waterbodies. Hobart, Tasmania AU.

Goebel, N.L., J.N. Kremer, and C.A. Edwards. 2005. A Simplified Approach to Modeling Keystone Processes that Lead to Hypoxic Events in Long Island Sound. Presented by N. Goebel at the 18th Biennial Conference of the Estuarine Research Federation, October 2005. Norfolk, VA.

Kremer, J. N. 2005. The case for simple and general estuarine models for ecosystem-based management. ERF Norfolk VA, Invited, special session on Ecosystem Based Management.

J.N. Kremer, Goebel, N.L., and C.A. Edwards. 2006. Imbalances Between Gross Primary Production and Community Respiration in Central and Western Long Island Sound. To be presented by Jim Kremer at the Estuarine Research Federation Conference, October 2006. Providence, RI.

Public Outreach

N.L. Goebel volunteered as a visiting scientist aboard the "Science Under Sail" public outreach expedition run out of the Monterey Bay Aquarium, where she discussed the importance of phytoplankton, and the deleterious effects of nitrogen loads, eutrophication, and hypoxia in coastal embayments (using LIS as an example). The aim of this educational science cruise is to increase public awareness about the type of research carried out in the ocean, and the types of impacts the public have on their oceans, leaving behind a positive message about environmental awareness of our oceans.

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