

HYDROLOGICAL IMPACTS ON WETLAND CARBON FLUX RESIDUALS

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ABSTRACT

Wetland vegetation often takes in more atmospheric carbon dioxide (CO₂) during photosynthesis than it releases during respiration and decomposition. On the global scale, wetlands help moderate atmospheric CO₂, the greatest contributor to anthropogenic climate warming. Carbon dioxide fluxes between the ecosystem and atmosphere measured at wetland sites help monitor the extent to which wetlands act as sinks, and sometimes sources, of atmospheric carbon and how their roles are changing over time. Precise model predictions of wetland carbon sequestration or expulsion are paramount to accurately diagnosing future concentrations of atmospheric carbon and the subsequent consequences to the climate system. However, significant model error exists in predicting these processes.

Moreover, wet regions such as temperate wetlands are predicted to become wetter and warmer due to anthropogenic climate change. The ensuing impact on wetland hydrology and nutrient cycling will further complicate the prediction of CO₂ fluxes. To determine whether or not hydrology currently plays a prominent role in prediction error, the residuals between high-frequency multi-year carbon dioxide flux measurements from a Wisconsin and two Canadian wetland sites and the corresponding predictions from a suite of nearly one dozen independent ecosystem models are compared to observed water table measurements. A correlation between hydrology and model error would indicate how models could be improved to better predict the relationship between climate change and wetland carbon cycling.

I. Introduction

Water table levels are expected to fall as a result of warming climate trends (Meehl et al 2007). Because the most warming is expected at higher latitudes, northern wetlands are likely to see subsequent decreases in water table heights. Changes in wetland hydrology may induce changes in wetland *net ecosystem exchange* (NEE), the rate at which carbon is entering or

leaving the atmosphere from the ecosystem, by changing the rate at which carbon is taken in through plant photosynthesis (*gross primary productivity*) and the rate at which the wetland releases carbon to the atmosphere through vegetative respiration and the release of previously stored carbon during the decomposition of plant matter by microorganisms, *ecosystem respiration* (Baldocchi 2008). Peatlands, in particular, have been estimated to hold between 19% to 33% or more of the world's soil-carbon reservoir (Bridgham et al 2006; Gorham et al 1991; Schuur et al 2008; respectively), representing a range of 260-450+ Pg of carbon.

Carbon Cycling and Water Table

A 2009 study by Ellis et al, published in *Ecological Engineering*, looked at the impact of water table draw-down on carbon fluxes and dissolved organic carbon (DOC). The study was conducted at a Welsh upland ombrotrophic bog, meaning that the site's main water and mineral sources are from precipitation, as opposed to ground or surface water. Sphagnum moss, dominant at this site, is often a prominent feature of bogs.

To setup the experiment, peat cores were collected from the site with care to avoid peat compaction (which would have an impact on the height of the water table relative to the peat's surface potentially negating the effect of the draw-down among other possibilities). The cores, or monoliths, were contained in plastic liners and were 11 cm in diameter with a 25-cm depth. The cores were closed on the bottom but open on the top to the atmosphere. The water table was kept at steady levels for all treatments. The water level was maintained at the vegetative surface for the controls and at 5 cm below the vegetative surface for the draw-down treatments. The treatment cores were allowed to acclimate for four weeks after being brought to an experimental facility before beginning draw-down, and then draw-down occurred over a 6-week period.

The results of the Ellis et al study showed DOC concentrations to decrease with water table drawdown. The authors conveyed that decreased DOC concentrations were expected to be converted to a positive net flux of carbon, but there was no significant change in carbon fluxes with water table draw-down. The authors cite a 1990, Tipping and Woof study to conjecture that this decrease may be caused by a decrease in plant root secretions or the adsorption of some DOC onto insoluble precipitates.

A 2008 study by Bridgham, et al, published in *Ecology*, used different water table heights and temperatures on samples from a bog and a fen in northern Minnesota, to see the effect of these variables on net carbon accumulation. The experiment used 54 separate plastic insulated tanks, or mesocosms, buried in the ground with an exposed area of 2.1 m² and a depth of about 0.6 m. Uniform, frozen blocks of peat were placed into the tanks, some tanks representing the bog and others the fen. While water table height initially affected many of the trials with wetter conditions in the bog tanks favoring carbon sequestration in the form of peat accumulation, the changing height of the peat layer in relation to the water level eventually overrode this effect; the water levels in each tank were kept at a steady distance from the lip of the tank, which means that the water table height – a measure of the distance between the peat surface and the water level – was allowed to fluxuate. As more peat accumulated, the relative water table height lowered. This allowed the sample to be dryer overall and lessened the effect that the excess moisture initially had on peat accumulation. As a result, the mesocosms reached a new equilibrium point between peat (carbon) decomposition and accumulation. This equilibrium point was independent of the initial water levels and was the same for each bog experiment showing that the equilibrium state is dependent on the peat composition and not the water level. However, because the excess moisture sequestered a net amount of carbon in accumulating peat

before equilibrating, both decreased water table levels and increased evapotranspiration expected with warming temperatures could cause a net release of carbon before again reaching equilibrium.

While both the fen and bog mesocosms showed peat gain with wetter conditions and peat loss with dryer conditions, the soil-carbon gain or loss from the bog samples was much more strongly correlated with water table than the fen (Bridgham et al 2008). The authors posit that this has a lot to do with the vegetative makeup of the bogs. According to Bridgham, et al, in bogs dominated by sphagnum moss (which is generally the case), the productivity and low decomposition rate of the moss with changing water table heights greatly determines the response of the bog's soil-carbon composition. However, in fens, there is not yet one clear determining factor. In the bog mesocosms of the Bridgham, et al, study, 77% of the net primary productivity (NPP) was that of the sphagnum moss, and this part of the NPP was responsible for 43% of the change in soil carbon composition, presumably based on correlation coefficients over all the bog experiments. The sphagnum moss grew best in experiments with dryer initial conditions, though declines in sphagnum moss paralleled both peat loss and decreasing water levels.

Another study, published in 2009 by Chivers et al, also looked at the effect of water table height on carbon sequestration in a wetland with sphagnum moss as one of its dominant vegetative species, though some key differences between the studies exist. The wetland used in the Chivers et al study is a rich fen in Alaska, meaning it has rich nutrient inputs from surface water, groundwater or both in addition to precipitation. Instead of using mesocosms, open top chambers (OTCs) were used. The OTCs were made of Lexan, a polycarbonate resin thermoplastic, which surrounded plots in the fen. There are no Lexan tops or bottoms to these structures, only sides. Unlike the mesocosms from Bridgham et al, water table of the surrounding area governs the water table in the small plots. Though the height and depth of these structures are not given, each OTC surrounded a 3-m² area of the fen and was used to take measurements, and in some of the plots, heat the air and soil. Larger, 120-m² plots were designated for three different water table categories: raised (flooded), lowered (drought), and the natural water table height of the fen as a control.

Natural water table fluxuations measured at the control site were used to fluxuate water table heights at the raised and lowered water table plots via solar powered bilge pumps after the water at the lowered water table site was diverted by a trough. The hydroperiods between the two years, shown in Figure 1, are very different. While the water table is fairly steadily near -10 cm, only deviating just over 10 cm more or less throughout 2005, the hydrological profile for 2006 has much more variation. The control hits its peak around 0 cm and drops down to almost -70 cm in August. The difference between the control and the treatments is also greater. While the raised and lowered water tables in 2005 were 9 cm above and 5 cm below the ambient water table, the 2006 levels were 11 cm above and 8 cm below the control. The control in 2006 also shows more variation than the treatments.

The percentage of sphagnum moss coverage initially ranged between 5 and 80%. When the vegetative coverage was surveyed after the experiment, the plots with lower water table were found to have the most dead sphagnum moss with reductions around 20%. Brown moss was reduced by 50%, and the positive correlation between sphagnum moss coverage and vascular plant coverage (Pearson correlation coefficient of 0.87) suggests vascular plant coverage was reduced as well.

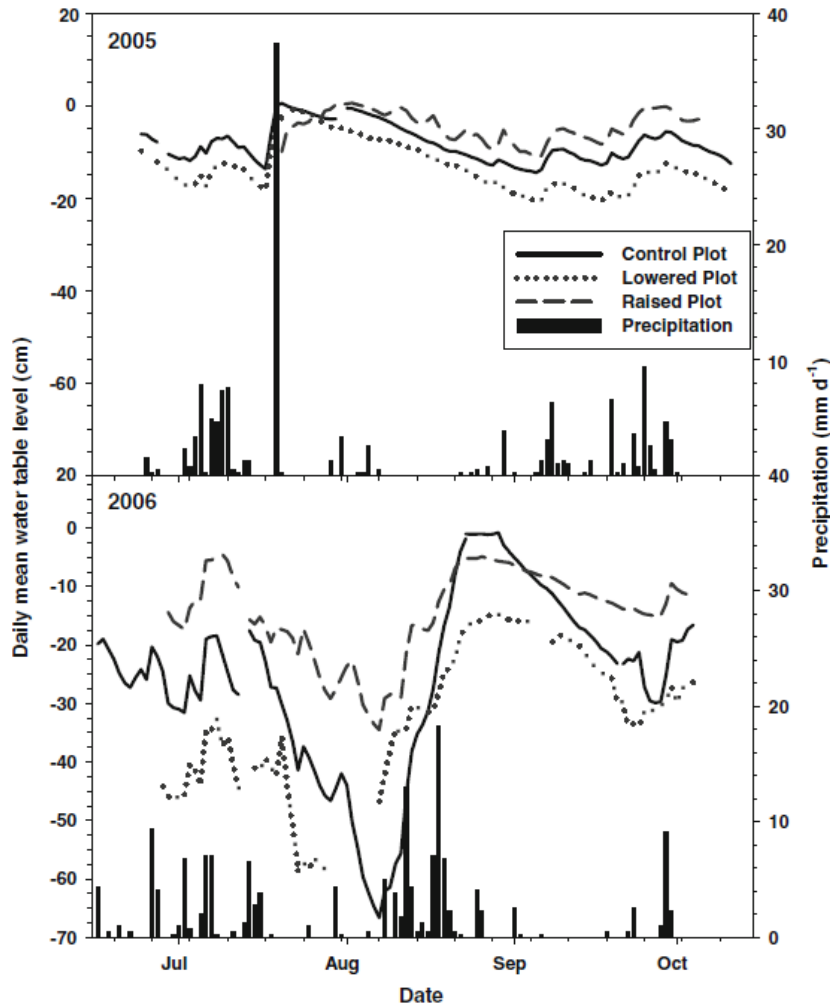


Figure 1 shows precipitation amounts per day and daily mean water table levels for each water table category in the study (Chivers et al, 2009).

Figure 2 shows the net ecosystem exchange (NEE), which is the net carbon flux into (+) or out of (-) the atmosphere. The components of the NEE are ecosystem respiration (ER) and gross primary productivity (GPP). NEE values for 2005 show the control site as a sink for CO₂. The raised and lowered water table categories have ER and GPP values that nearly cancel though, the magnitudes of both the GPP and the ER were greater for the lower water table heights. Although the 2005 values for the raised water table heights represent the highest water table heights in the study, the 2006 treatment with raised water table heights shows the greatest carbon sink across all the treatments and controls. Another unexpected detail is that the magnitudes of the GPP and ER decreased between 2005 and 2006 in the control and lowered plots but increased in the raised plot.

The final study was conducted at a poor fen in Quebec, “poor” referencing the fen’s nutrient supply and being similar to, if not synonymous with, “ombrotrophic” as used in the Ellis et al study. The landscape of the poor fen studied by Strack et al (2006) was a pool-ridge complex. Two pools were chosen and one drained using a ditch to a lower pool 8 years before the study. The total drainage for the treatment pool was about 20 cm. The pools were further partitioned by three types of microforms, hummocks (small hills), lawns (small flat areas), and hollows (mostly small open-water depressions). Water table was manually measured every week, while Plexiglass chambers were set up to measure CO₂ fluxes.

Between August 2001 and 2002, there were differences in vegetation between the control and the drained pools which varied by microform. Sphagnum moss was less at the drained hummock and lawn microforms than the controls but more at the drained hollows. Herbaceous plant cover was about the same at drained hummocks but greater at drained lawns and hollows. The net ecosystem exchanges over the entire study period from July 2001 to September 2002 were 445, -164, and 118 g C m⁻² at the hummocks, lawns, and hollows, respectively, at the control site. At the drained site, their respective values were 1321, 228, and -38 g C m⁻². Carbon sequestration was reduced by drainage at hummocks and lawns but increased at hollows.

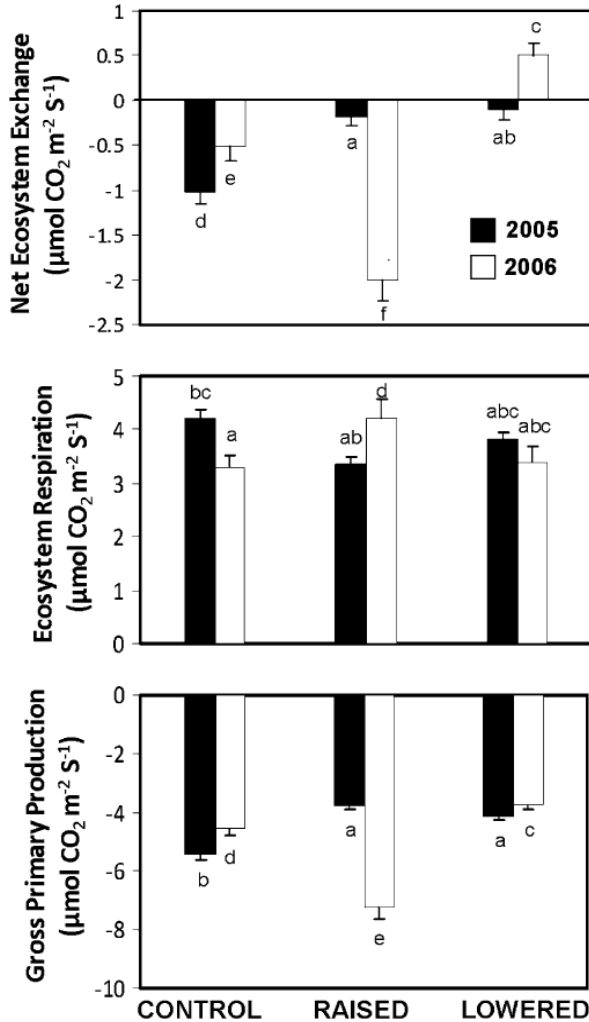


Figure 2 shows the carbon flux results of the Chivers et al, 2009, study. The plots do not use the same scale. The black bars show values for 2005, a warmer, wetter year with more stable water levels, while the white show values for 2006 (Image from Chivers et al, 2009).

The Bridgman et al (2008) study presents plots showing a positive correlation between soil-carbon gain and water table depth. Though the net ecosystem exchange is not shown here, decreases in soil-carbon suggest greater carbon fluxes into the atmosphere, i.e. an increase in NEE with lower water table depth. Like the Ellis et al study, the water table was kept constant; however, the water table was kept constant relative to the lip of the container which allowed the relative water table to fluxuate with changes in the peat. Increases in NEE are likely to stop after the system equilibrates to the changed absolute water table height.

In contrast, the Chivers et al (2009) study varied the treatment water table heights following the natural fluxuations at the control site. Future work focusing on water table variability and NEE would aid in understanding this study better. The lowest NEE was found in the plots with raised water table levels in 2006 but not at the time of the greatest water table heights, which occurred the previous year. Likewise, the study by Strack et al (2006) showed greater levels of NEE under drought conditions, which is consistent with previous findings. However, NEE was decreased in small open pools of water.

The Bridgham et al (2008) study showed changing sphagnum moss coverage to be a proxy for changing soil-carbon levels in environments where the moss is one of the dominant vegetative species. While both moss coverage and sphagnum moss decreased with falling water table heights, the highest amounts of sphagnum moss were found where water table levels were initially driest suggesting a complex relationship between these three variables. However, dry conditions in the Bridgham et al study refer to water table depths only 5-10 cm below the peat surface, levels considered moist in the last two studies.

Dry conditions for subsequent studies range between 15 and 65 cm below the peat surface. Chivers et al (2009) found sphagnum moss to be more prevalent in the more moist conditions found in the control and raised water table treatments. Strack et al (2006) also found the highest moss coverage in a microform with higher relative water table levels (hollows) but in the drained treatments of these microforms. As seen in the NEE from the Chivers et al (2009) experiments, the wettest conditions do not necessarily provide the most productivity. The conversion of the drained hollows from sources to sinks of carbon alongside the only increase in sphagnum moss seen in the study is consistent with the relationship between sphagnum moss and NEE found in Bridgham et al (2008). Future research in optimal water table depths for sphagnum moss growth in temperate wetlands would aid in deducing which moist regions of these wetlands may become more productive in future years.

Though recent studies indicate but have not yet defined an upper boundary in water table height for optimal carbon sequestration, carbon sequestration is generally greater with higher water table heights. Though lower water table heights initially induce a flux of carbon out of the ecosystem to the atmosphere, the ecosystem may be able to equilibrate back to a carbon sink provided the absolute water table depth remains constant. Vegetative coverage, and that of sphagnum moss in particular, is generally positively correlated with both NEE and water table depth.

Falling water table heights as wetlands warm will likely increase NEE unless the change is small (5 cm) as seen in the Ellis et al (2009) study. In this case, peat subsidence may allow the relative water table to remain about the same. Though the net effect with larger decreases in water table heights is likely to be an increase in atmospheric carbon, some currently moist regions may become more productive with falling water table height. While some of these factors may be included in current terrestrial carbon cycle models, others may not and may impact model error.

II. Methods

Wetland Sites

Carbon fluxes at three wetland sites were studied. The Western Peatland, the westernmost site, is a fen located in central Alberta and is primarily composed of spruces, larch trees, and betula and ledum shrubs (Fluxnet-Canada, <http://www.fluxnet-canada.ca>). Of all three

sites, this site receives the least amount of precipitation (507.3 mm, annually). However, as a fen, the Western Peatland also receives water inputs through groundwater and surface water inputs. Data for the Western Peatland was available for the time period between 2004 and 2008. The second wetland site, Lost Creek, is located east of the Western Peatland in northern Wisconsin. Lost Creek is considered an alder-willow shrub fen and gathers 771 mm annual precipitation, on average, in addition to surface and groundwater inputs (AmeriFLUX, <http://public.ornl.gov/AmeriFLUX>). Data analyzed for Lost Creek spans from 2001 to 2007. The last site is Mer Bleue (also called the Eastern Peatland), a raised bog in southern Quebec, which is fed primarily by the average 910 mm of annual precipitation it receives. The dominant vegetation at Mer Bleue is mostly shrubs and sphagnum moss (Fluxnet-Canada). Data was available and analyzed for Mer Bleue between 2000 and 2006.

Observed Carbon Fluxes

Observations of NEE were gathered from FLUXNET at the Oak Ridge National Laboratory Data Active Archive Center website (ORNL DAAC, <http://daac.ornl.gov>). Half-hourly data for the Western Peatland, Mer Bleue and Lost Creek were gathered from FLUXNET component networks Fluxnet-Canada and AmeriFLUX and converted to monthly averages. NEE is derived using the eddy covariance method, while GPP is calculated from MODIS data. The eddy covariance method measures the covariance between vertical motions and gas concentrations on a horizontal plane (Baldocchi et al 2008). The eddy covariance method assumes flat terrain, steady weather conditions, and uniform and expansive vegetation upwind of the flux tower. After a year of measurements, about 5% error is introduced into the measurements from atmospheric turbulence and vegetative variation. An additional 5-10% is introduced from the instruments used. An estimated 20-30% of the data for each year of FLUXNET observations is removed during the quality control process. For the observations used in this study, gaps were filled using the median u^* correction. This correction accounts for underestimates of CO_2 due to increased nighttime stability.

Modeled Carbon Fluxes

Of many groups participating in the North American Carbon Program synthesis project, six utilized input data for all three sites in their models. These models are the Simple Biosphere Model, version 3 (SiB3), the Terrestrial Ecosystem Model (TECO), the Lund-Potsdam-Jena Dynamic Global Vegetation Model (LPJ), the Organizing Carbon and Hydrology in Dynamic Ecosystems model (ORCHIDEE), the Simplified Simple Biosphere Model, version 2 (SSiB2), and the Combined Simple Biosphere and Carnegie-Ames-Stanford Approach Model (SiBCASA). Metadata for all of the models except SiBCASA is synthesized from the ORNL DAAC website (http://daac.ornl.gov/SURVEY8/survey_results.shtml).

SiB3

The SiB3 model is from Colorado State University. The model initiation date for the period from January of 2000 through December of 2006 was 1 January 2000, initializing alongside data collection. The model had an hourly temporal resolution with an end date of 31 December 2006. The Leaf Area Index (LAI) was derived from remotely-sensed fraction of photosynthetic radiation (fPAR) from Moderate Resolution Imaging Spectroradiometer (MODIS) data, while vegetation and soil characteristics were taken from the International Geosphere-Biosphere Programme Data and Information System (IGBP-DIS). Ten soil layers

were used, and the thicknesses of the individual layers increased with increasing depth. Texture classifications were assigned to each layer. Disturbances by crops and harvests were included through observations and simulations, respectively. Precipitation, temperature, humidity, wind speed, and solar radiation were included using the North American Regional Reanalysis (NARR).

SiB3 calculates NEE as the difference between GPP and ER. GPP is modeled using an enzyme kinetic model with function inputs for air temperature, soil moisture, surface incident short- and longwave radiation, vapor pressure deficit, atmospheric CO₂, leaf nitrogen and fPAR. In order to calculate ER, the model first calculates and forces an annual balance between heterotrophic and autotrophic respiration. Heterotrophic respiration is calculated using a zero-order model, while autotrophic respiration is taken as a fraction of the GPP. Evapotranspiration (ET) is derived from air and soil temperature, precipitation, surface incident shortwave radiation, specific humidity, soil texture, and soil moisture. Soil moisture is first derived from surface runoff, subsurface drainage, water vapor diffusion through the soil, soil texture, air and soil temperature, precipitation, surface incident short- and longwave radiation, specific humidity, and evaporation.

TECO

TECO is from the University of Oklahoma. As seen with SiB3, the model initiation and end dates also align with the data collection initiation and end dates with an hourly temporal resolution. However, unlike SiB3, TECO simulates *dynamic* carbon pools. Of eight total dynamic carbon pools, three describe vegetation: leaves, woody vegetation, and fine roots. The dynamic soil carbon pools describe metabolic and structural litter in addition to fast, slow and passive soil organic matter. TECO also utilizes ten soil layers; the first five layers are 10 cm thick while the second five are each 20 cm in depth. The canopy is predicted using air temperature, precipitation, soil moisture, surface incident shortwave radiation, and vapor pressure deficit.

NEE is calculated as before as the difference between GPP and ER. In this case, GPP is simulated with a stomatal conductance model and contains the parameters utilized by the kinetic energy model in SiB3 with the exception of longwave radiation, leaf nitrogen and fPAR. Heterotrophic respiration is instead calculated using a first or greater order model, while autotrophic respiration is explicitly calculated using air temperature and vegetation carbon. ER is then the sum of the heterotrophic and autotrophic respiration predictions. For TECO, ET is taken as the measured evaporation. Soil moisture is derived from the same parameters as those utilized by SiB3 with the exception that TECO does not include water vapor diffusion through the soil, air temperature, surface-incident short- and longwave radiation, and specific humidity.

LPJ

The LPJ model is from the Potsdam Institute for Climate Impact. The model simulation has a daily temporal resolution. Like TECO, the LPJ model also contains dynamic carbon pools, though they are kept steady-state from the initialization date, 1 January 1000, through 1 January 1901. The five dynamic carbon pools of the LPJ model describe vegetation, litter, and soil carbon pools in addition to intermediate and slow soil organic matter pools. Two soil layers are simulated, and canopy cover is derived from soil moisture and vegetation carbon. Several disturbance regimes are included for LPJ. Disturbances from fires and harvests are input from observations, while use and crop disturbances are input from simulations.

As seen with TECO, the LPJ model uses a stomatal conductance model to predict GPP, though the number of parameters used better reflects the makers of SiB3. TECO GPP is derived from air temperature, precipitation, soil moisture, surface incident shortwave radiation, actual and potential evaporation, atmospheric CO₂, and fPAR. In this case, both heterotrophic and autotrophic respiration are calculated explicitly – heterotrophic respiration from soil temperature, soil moisture and soil carbon, and autotrophic respiration from air temperature, soil temperature, and vegetative carbon – and these are added to find total ER. ET is derived from air temperature, precipitation, surface incident shortwave radiation, actual and potential evaporation, and soil moisture. Soil moisture is also computed a little differently than the others and utilizes irrigation and potential evaporation in addition to surface runoff, subsurface drainage, soil texture, precipitation, and actual evaporation.

ORCHIDEE

ORCHIDEE comes from the Institut Pierre Simon LaPlace in France. The initialization date for the data studied here is 1 January 1991, and the temporal resolution is hourly. Like the previous two models, ORCHIDEE contains dynamic carbon pools. However, all eight of the dynamic carbon pools are kept at steady-state conditions from the period between 1901 and 1910 and simulated for 2000 years from 1 January 1901. The eight dynamic vegetation carbon pools are labeled as leaf, fine roots, heartwood below and heartwood above, sapwood below and above, fruit, and carbohydrate reserves pools. The eight dynamic soil carbon pools are labeled for metabolic litter above and below the soil surface, structural litter above and below the soil surface, coarse woody litter, and active, slow and passive soil carbon. However, multiple soil layers are not used. The canopy cover is predicted from several parameters: air temperature, soil moisture, surface incident short- and longwave radiation, vapor pressure deficit, atmospheric CO₂, and vegetative carbon. Observed uses and simulated harvest disturbances are also included.

In addition, meteorological variables are included as seen in the SiB3 metadata, though ORCHIDEE uses a combination of the forecasts from the United Kingdom's University of East Anglia Climatic Research Unit (CRU) and the National Centers for Environmental Prediction (NCEP). As seen with SiB3, ORCHIDEE uses the enzyme kinetic model to calculate GPP, though the inputs are somewhat different. GPP for ORCHIDEE utilizes the same inputs as SiB3, with the exception that relative humidity and leaf age are included while longwave radiation, vapor pressure deficit, and fPAR are not. The heterotrophic respiration is calculated by a first or greater order model as seen with TECO. Autotrophic respiration is explicitly calculated, as has mostly been the case, though it is derived using only the air temperature parameter. ET is derived using similar functions as with the SiB3 model, though longwave radiation and vapor pressure deficit are included while soil texture and specific humidity are not. Soil moisture is also similar to that of SiB3, though the ORCHIDEE model does not include water vapor diffusion through the soil, air temperature or evaporation.

SSiB2

SSiB2 comes from Princeton University and is the simplest model of the six under study. The time resolution is half-hourly and the model initialization date is 1 January 1973. Three soil layers with varying texture descriptions are also included, though the model lacks other kinds of regional input. SSiB2 calculates GPP using a subset of parameters from the SiB3 model input; relative humidity is used instead of specific humidity, while longwave radiation, vapor pressure

deficit and leaf nitrogen are not included. LAI is derived from fPAR and also used to calculate GPP. Autotrophic respiration is explicitly calculated using the same parameters as GPP and appears to be assumed equivalent to ER. ET is computed using air and soil moisture, surface incident short- and longwave radiation, vapor pressure deficit, soil texture, and soil moisture. The soil moisture is calculated the same way as for SiB3, though SSiB2 uses hydraulic redistribution instead of precipitation. This model produced anomalously large residuals relative to the other five models and was discarded for the purposes of this study.

SiBCASA

SiBCASA combines the photosynthetic properties of SiB, version 2.5, with the dynamic carbon pools of the Carnegie-Ames-Stanford Approach in order to allow SiB to be effective over long time periods (Schaefer et al 2008). While many of the functions seen in SiBCASA are similar to that discussed for SiB3, SiBCASA simulates 13 dynamic carbon pools: a storage pool for starch; leaf biomass; fine root biomass; woody biomass; coarse woody debris; surface metabolic, microbial and structural pools; and soil metabolic, structural, microbial, slow and armored pools. Like SiB3, LAI is derived from fPAR which, in turn, is derived from MODIS data. However, the vegetative distribution is not taken from the IGBP-DIS but derived from the Normalized Difference Vegetation Index (NDVI), which is also from MODIS data. Soil properties used in SiBCASA are still taken from IGBP.

In order to calculate GPP, SiBCASA couples both the stomatal conductance model and the enzyme kinetic model for C₃ plants utilized separately by previous models and also couples them with a C₄ photosynthesis model. In this case, SiBCASA can be set up to transition between the enzyme kinetic model and the C₄ photosynthesis model to reflect the same transitions in the plant cover through the growing season. Autotrophic respiration is now explicitly calculated with the addition of the starch storage pool, though other aspects of GPP and NEE calculations are similar to the SiB2.5, and presumably, SiB3 models.

Water Table Observations

Water table observations were taken at Lost Creek using pressure transducer systems (Sulman et al 2009). Water table height is defined for this study as the height of the water in relation to the soil surface where positive values indicate standing water. Observations were gathered for Mer Bleue and the Western Peatland as well. In order to avoid the added computational complication of frozen water on water table heights, only the summer months were analyzed and include June, July and August.

III. Results

Residuals are shown in Figures 3 and 4 and were calculated by subtracting observed values from modeled ones. Positive residuals show overestimates by the models. Residuals for GPP and ER both show positive trends indicating better model performance at lower water table levels. However, these overestimations cancel out to some degree, resulting in NEE values with little error or pattern. Mer Bleue appears to be an exception, as the ER residuals are about 1 $\mu\text{mol}/\text{m}^2/\text{s}$ greater in magnitude than the GPP residuals resulting in an underestimate in NEE at higher water table levels.

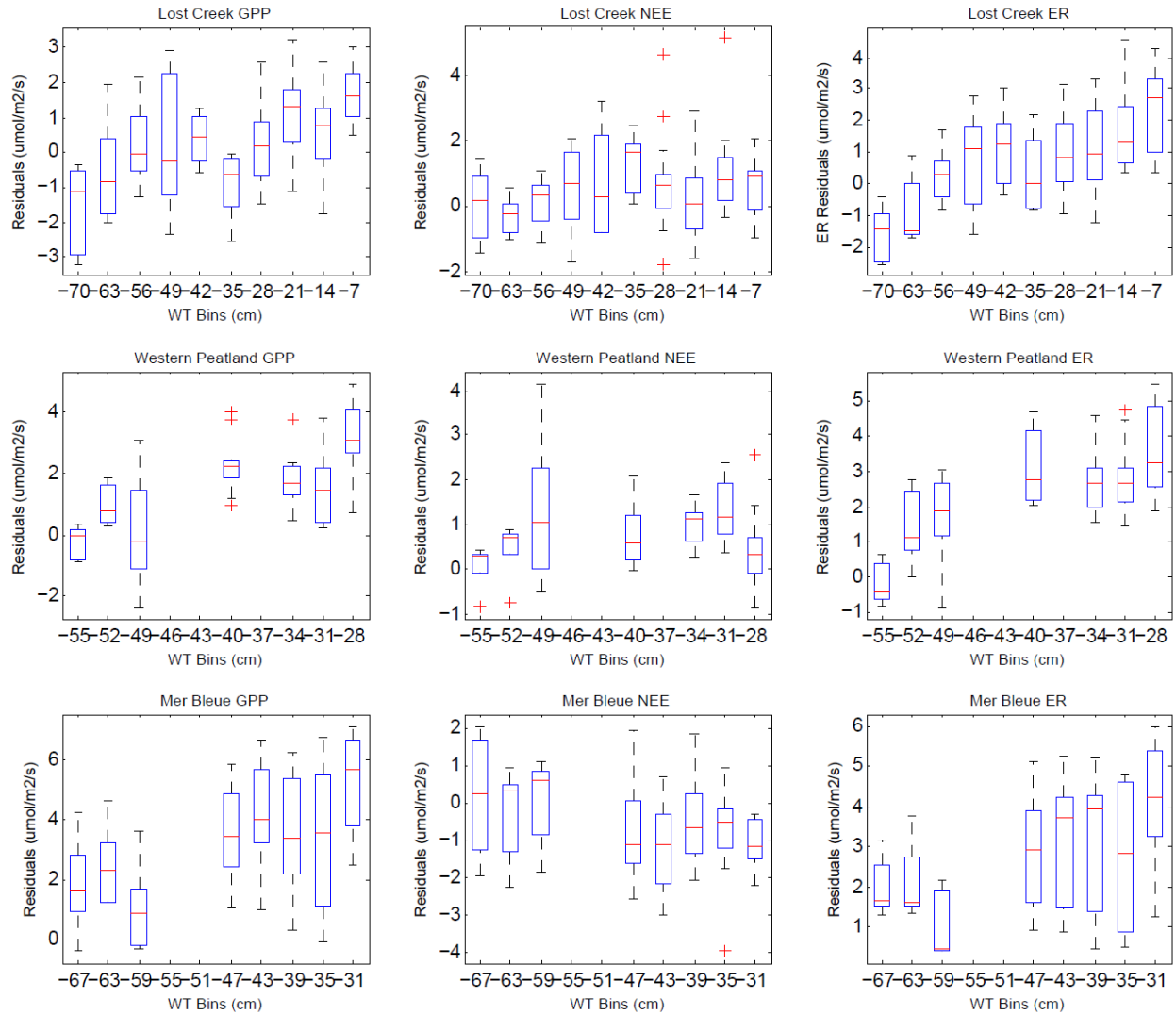


Figure 3 shows box-and-whisker plots for the model residuals. Only summer (June, July, and August) values were included in the residual plots. Each site varies in the years studied: Lost Creek, 2001-2007; the Western Peatland, 2004-2008; Mer Bleue, 2000-2006. Individual boxes come from bin-averaged data with variable numbers of data points in each one. Red lines indicate the mean for each bin; the top of the box indicates the upper 75th percentile, and the bottom of the box, the 25th percentile. The box whiskers extend to the maximum and minimum data points in each bin with the exception of outliers which are shown as red plus signs.

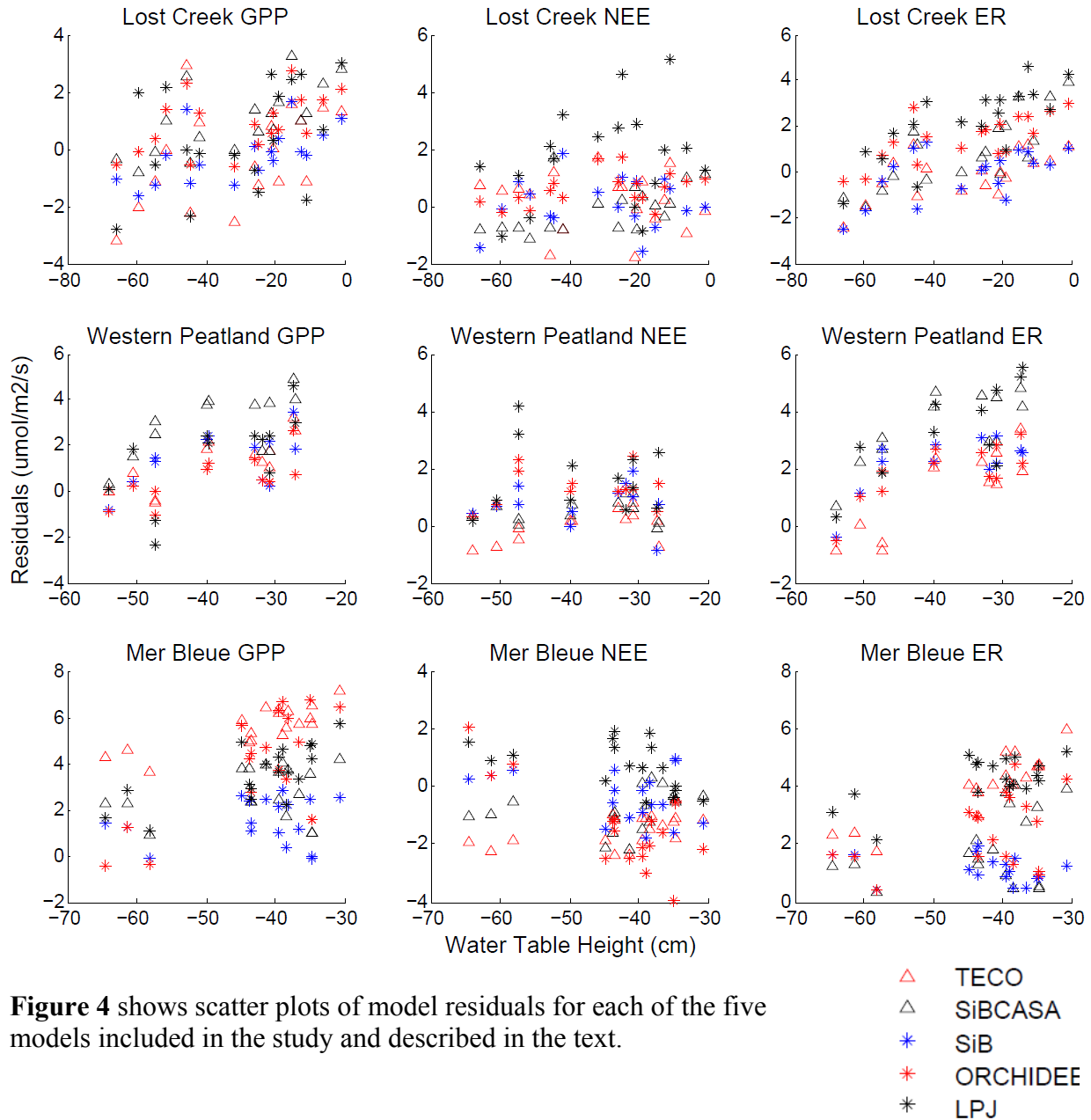
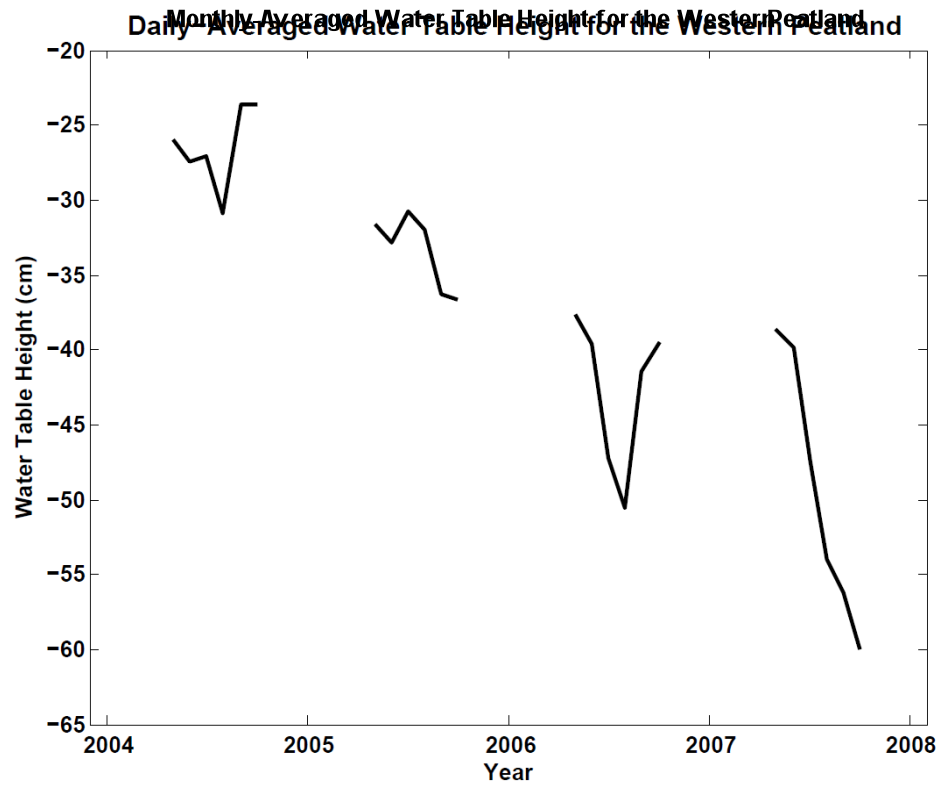
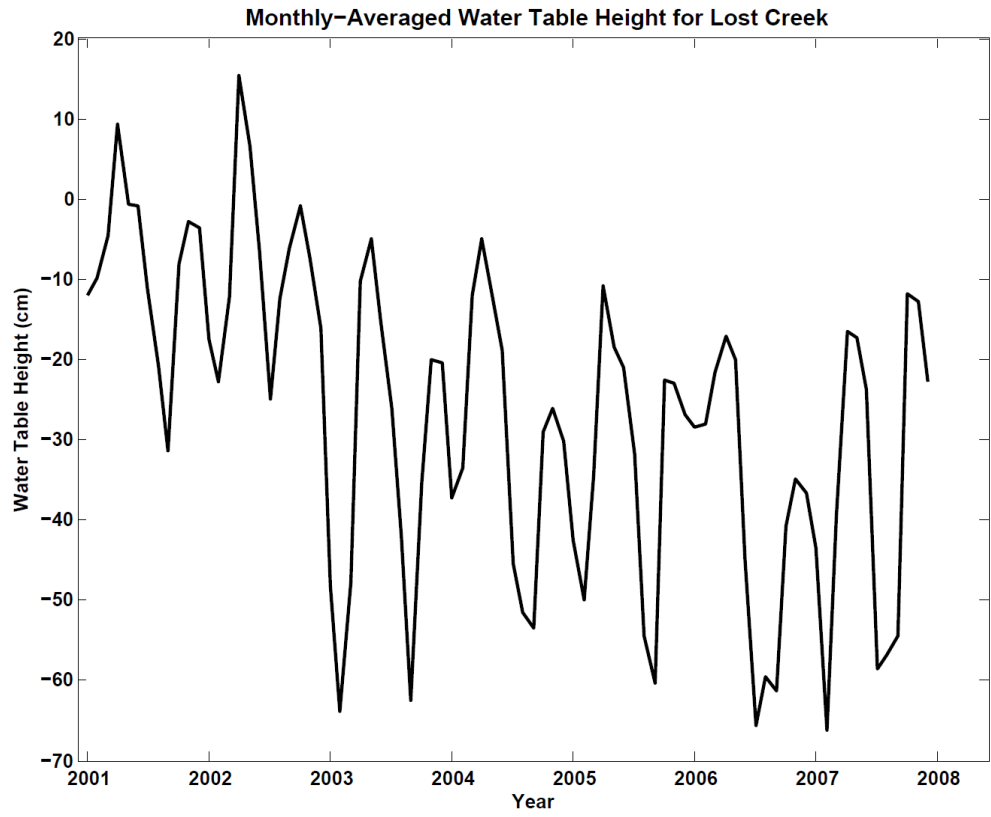


Figure 4 shows scatter plots of model residuals for each of the five models included in the study and described in the text.

Different model residual trends are shown in Figure 4. While SiB3 (shown in blue stars) appears relatively accurate at each site for each parameter and LPJ relatively inaccurate at each site, the other three models vary. TECO and ORCHIDEE overestimate GPP at Mer Bleue and underestimate ER at the same site leading to some of the largest underestimates in NEE at the bog. However, the same two have some of the lowest residuals at the Western Peatland. SiBCASA tends to perform about average with the exception of its performance at the Western Peatland where large errors in both GPP and ER roughly cancel to produce some of the best overall NEE estimates at that site.



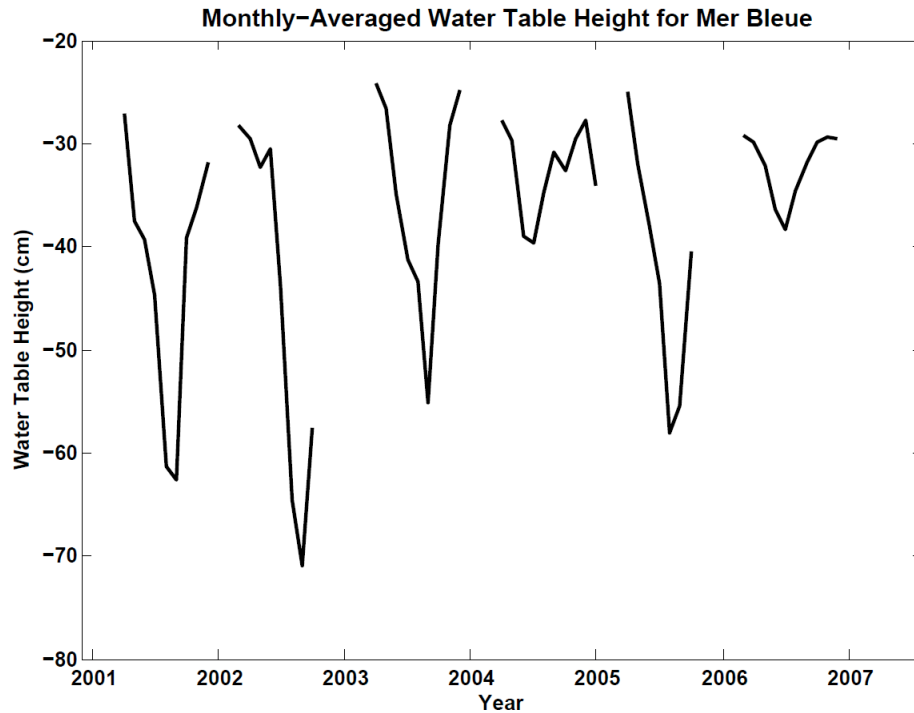


Figure 5a-c show water table heights for each site. Some data is missing from the Western Peatland and Mer Bleue.

Different trends in water table are seen at each site. Lost Creek shows a highly variable water table profile with an overall steep drop from depths near the peat surface to half a meter below it. The trend at the Western Peatland falls more steadily but is less steep. Though the overall average water table heights do not appear to be rising, less extreme water table minima occur at Mer Bleue over time indicating higher water table depths overall.

IV. Discussion

SiB3 performs the best at each site over the other four models from this study and has the most accurate performance of any site at Mer Bleue. Though SiB3 does not include dynamic carbon pools, the time frame under study may be too small for there to be significant changes in the size carbon pools and subsequent consequences. Based on the positive trends shown between GPP and ER residuals and water table depth, better model performance might be expected from SiB3 at lower water table depths. This is the case for SiB3 at Lost Creek and the Western Peatland but not at Mer Bleue where model performance remains relatively constant.

One major difference between SiB3 and most of the other models is that MODIS data is used to diagnose vegetative cover. We have already seen that sphagnum moss tends to make NEE correlated with water table depth. SiB3 takes a larger numbers of parameters than most of the models into account in order to diagnose soil moisture which it then uses to predict GPP, NEE and ET. Sphagnum moss has also already been shown to favor conditions which are initially drier (Bridgham et al 2008), as seen at Mer Bleue in Figure 5c.

If the MODIS-derived assessment of vegetative cover is aiding the performance of SiB3 at the bog site, SiBCASA would also be expected to perform well there which it does. Though

not as accurate as SiB3, SiBCASA shows similar groupings of data points in Figure 4 with the exception of ER residuals. Both SiBCASA and ORCHIDEE have two separate groupings at higher water table depths, one which follows along with SiB3 and another with a positive trend similar to that of TECO and LPJ. One unique similarity between SiBCASA and ORCHIDEE is that they contain the two largest numbers of dynamic carbon pools at 13 and 16, respectively, eight of which describe vegetation carbon pools in both cases. The dynamic carbon pools of both SiBCASA and ORCHIDEE do not follow a steady-state assumption through the time frame of interest, though the LPJ model allows the dynamic carbon pools to change rates as well but does not exhibit the same divide.

Another similarity between SiBCASA and ORCHIDEE is that they utilize the enzyme kinetic model in order to diagnose GPP. While SiBCASA also uses the stomatal conductance model and a C4 photosynthesis simulation, the productivity models change during the summer season. A look at individual months may for a larger number of bog sites may clarify this feature in the data.

IV. Conclusions

Model performance generally improves with decreasing water table height. However, in bogs with sphagnum moss, model performance may improve for higher water table values. With some exceptions, the models do not appear to vary in a consistent way, likely because their input values and functions do not vary in a consistent way. Future work in systematically varying model features with the use of controls would greatly aid in diagnosing more specific features of the model which aid or hinder accurate assessment of wetland hydrology, especially at higher water table heights.

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