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RESEARCH ARTICLE

Modeling dissolved organic carbon in subalpine and alpine lakes with GIS and remote sensing

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Abstract Current global trends in lake dissolved organic carbon (DOC) concentrations suggest a need for tools to more broadly measure and predict variation in DOC at regional landscape scales. This is particularly true for more remote subalpine and alpine regions where access is difficult and the minimal levels of anthropogenic watershed disturbance allow these systems to serve as valuable reference sites for long-term climate change. Here geographic information system (GIS) and remote sensing tools are used to develop simple predictive models that define relationships between watershed variables known to influence lake DOC concentrations and lake water color in the Absaroka-Beartooth Wilderness in Montana and Wyoming, USA. Variables examined include watershed area, topography, and vegetation cover. The resulting GIS model predicts DOC concentrations at the lake watershed scale with a high degree of accuracy ($R^2 = 0.92$; $P \leq 0.001$) by including two variables: vegetation coverage (representing sites of organic carbon fixation) and areas of low slope (0–5%) within the watershed (wetland sites of DOC production). Importantly, this latter variable includes not only surficially visible wetlands, but "cryptic" subsurface wetlands. Modeling with Advanced Land Imager satellite remote sensing data provided a weaker relationship with water color and DOC concentrations ($R^2 = 0.725$; $P \leq 0.001$). Model extrapolation is limited by small sample sizes but these models show promise in predicting lake DOC in subalpine and alpine regions.

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Introduction

Dissolved organic carbon (DOC) plays a fundamental role in aquatic ecosystem structure and function (Carpenter et al. 1998; Williamson et al. 1999, 1996; Cole et al. 2006; Pace et al. 2007). Specifically, small oligotrophic to mesotrophic glacial lakes are heavily dependent on DOC quantity and quality for attenuation of ultraviolet and visible light (Morris et al.

1995; Fee et al. 1996; Gunn et al. 2001), although in high-elevation/low-DOC lakes (<0.3 mg/l DOC) phytoplankton may play a major role in attenuating ultraviolet radiation (Laurion et al. 2000; Sommaruga and Augustin 2006). As a result this class of lakes shows a strong relationship between DOC concentration and light absorbance or attenuation (Williamson and Zagarese 2003).

Because a large portion of aquatic DOC is terrestrially derived, DOC concentrations provide valuable information about the changing conditions in the surrounding terrestrial landscape as well as atmospheric processes (Williamson et al. 2008). Understanding DOC concentrations alone provides insight on processes such as climate change, hydrology, and vegetation for examples. In several regions of North America and Europe long-term trends of increasing DOC concentrations have been reported (Striegl et al. 2005; Evans et al. 2006; Monteith et al. 2007). In contrast, decreases in riverine export of DOC have been observed in other regions such as the Yukon River Basin (Striegl et al. 2005). Remote sensing and GIS provide valuable tools to measure DOC across broad geographic regions and help better understand current regional trends of complex ecological processes.

In most temperate and boreal landscapes the concentrations of DOC in inland waters are regulated by a wide variety of watershed characteristics including the quantity and type of vegetation, watershed slope, and particularly the extent and nature of wetlands (Engstrom 1987; David and Vance 1991; Frost et al. 2006; Rae et al. 2001; Rice 2002; Williamson et al. 2001; Canham et al. 2004; Xenopoulos et al. 2003). Hydrologic characteristics in turn determine how much of that carbon will be exported to downstream sites (Boyer et al. 2000, 1997; Inamdar et al. 2004; Ogawa et al. 2006; Worrall et al. 2002). DOC concentrations can also be influenced by temperature fluctuations (Cooper et al. 2007; Harrison et al. 2008; Hudson et al. 2003; Striegl et al. 2005) and changes in atmospheric SO_4 deposition (DeWit et al. 2007; Evans et al. 2006, 2005; Monteith et al. 2007). Ultimately, no single set of watershed characteristics can be used to predict DOC concentrations across broad geographic regions (Xenopoulos et al. 2003).

The two most fundamental processes leading to DOC accumulation within a watershed are carbon fixation by vegetation (primarily terrestrial in most cases) and slow decomposition of dead organic carbon leading to the accumulation of DOC rather than remineralization of fixed carbon to CO_2. In lower elevation landscapes most areas of a given watershed will contribute to both carbon fixation and DOC generation to different degrees. Alternatively, high elevation watersheds are generally comprised of landscape elements with strongly contrasting potential contributions to organic carbon fixation and DOC generation. For example, a substantial portion of alpine landscapes is often covered in rock and ice. In addition, steep, well-drained, and well-aerated slopes provide conditions that accelerate decomposition and generate minimal DOC, while low-slope regions with inundated soils and low flow rates create conditions that combine with low temperatures to slow decomposition rates and favor DOC generation. Alpine watersheds thus lend themselves well to quantification of contrasting landscape types with GIS and remote sensing tools that can estimate potential contributions to DOC pools and fluxes.

Creed et al. (2003) identified sites of enhanced DOC using topographic watershed characterization. Saturated soils below the surface create anoxic conditions, which are optimal for DOC enhancement (Creed et al. 2003; Ogawa et al. 2006; Worrall et al. 2002). Further, areas with low slope may enhance DOC export by flushing upper soil levels with rising groundwater. Additional flushing of DOC comes from subsurface flow, which can reach deep into soil layers. In lower elevation well-forested regions such as the Adirondacks of New York State spatially explicit models have identified wetlands, forests, roads, flow accumulation, and flow-path distances as important predictors of DOC in lakes with a fair degree of accuracy ($R^2 = 0.546$; Canham et al. 2004). Inclusion of "cryptic wetlands", regions of the landscape with low slope that may have relatively inundated soils but no surficially visible wetland habitat, improved prediction of DOC export in the Algoma Highlands of central Ontario ($R^2 = 0.85$–0.88; Creed et al. 2003). Here we incorporate the concept of cryptic wetlands to assess the ability of two major landscape categories to predict DOC concentrations in high elevation lakes in the Absaroka-Beartooth Wilderness region of Montana-Wyoming, USA. We found that DOC concentrations in this region of highly contrasting landscapes can be predicted with a high degree of accuracy with just two major and often overlapping landscape categories: (1) regions that generate fixed carbon, defined as all areas with any type of vegetation visible with remotely sensed imagery, and (2) regions likely to generate DOC from this fixed carbon, wetlands and cryptic wetlands defined as all areas with low slope (0–5%).

Lakes display differences in water color as a function of DOC concentration, source, and photochemical history that may be visible in remotely sensed imagery (Hirtle and Rencz 2003; Nelson et al. 2003; Kutser et al. 2005a, b; Witte et al. 1982). Commonly available and widely used satellite imagery, such as Landsat data, have been sufficient only to identify broadly classified differences in lake water color (Hirtle and Rencz 2003; Kutser et al. 2005a; Nelson et al. 2003). Kutser et al. (2005a) compared remote sensing data sources with spectral absorbance measurements in lakes of Sweden and Finland. Data from the Advanced Land Imager (ALI) sensor onboard the EO-1 satellite provided the best measurement of spectral absorbance because of the 16-bit radiometric resolution. Less sensitive data sources, such as Landsat (8-bit) and Ikonos (11-bit), introduced noise into relationships with increasing DOC concentrations.

Here we measure the success of independent models at estimating lake DOC concentrations and spectral absorbance at select wavelengths. This study is part of a larger effort to understand nitrogen deposition, climate change and DOC impacts in the Absaroka-Beartooth Wilderness in Montana and Wyoming (Saros et al. 2003; Doyle et al. 2005; Cooke et al. 2006).

Methods

Our research methods involve creation of two independent models based on sampling of DOC concentrations in 19 lakes within the Absaroka-Beartooth Wilderness. The first model relates ALI reflectance values to sampled DOC concentrations and spectral absorbance values. The second model relates watershed variables in a GIS to sampled DOC concentration and spectral absorbance values.

Study area

The Absaroka-Beartooth Wilderness is located just northeast of Yellowstone National Park and is part of the Gallatin and Custer National Forests. The study area, a small (700 km^2) section of the Absaroka-Beartooth Wilderness, is home to >2,000 lakes according to the 2007 1:24000 USGS National Hydrography Dataset (NHD). Elevation within the study area ranges from 1,900 to 3,900 m above mean sea level with the tree line at about 3,100 m (USGS 2007 National Elevation Dataset). Land cover ranges from bare rock and perennial ice/snow to coniferous forests at lower elevations. The ice-free growing season varies depending on elevation and topography, but is generally limited to the summer months. Runoff within the study site is typically generated by summer snowmelt controlled by elevation and slope aspect. Overall, the topographic ruggedness and elevation of the Beartooth Plateau provide a study area with low human impact and oligotrophic lakes having generally low DOC concentrations (<3 mg/l; Fig. 1).

Field sampling and laboratory analyses

We sampled 20 lakes from July 2 to 13, 2007 in the Absaroka-Beartooth Wilderness. We selected lakes within a range of DOC concentrations representative of the area and also by their proximity to accessible field sites that are under ongoing study. We collected water samples from within the mixed layer, between 0.5 and 3 m deep within the pelagic region from a small rubber raft when possible or otherwise from the littoral area of the lake when pelagic collection was not possible. Water samples were immediately filtered through a 0.7 μm Whatman GF/F filter and stored in 40 ml glass bottles. All samples remained cold and dark prior to shipment to Miami University where they were analyzed for 2 weeks post-sampling for DOC concentration and a range of spectral absorbance values. DOC concentration was measured using a Shimadzu TOC-Vcph analyzer run in regular sensitivity mode. The spectral qualities of DOC are highly variable as a function of DOC source (allochthonous vs. autochthonous) and in-lake processes such as photobleaching (Morris and Hargreaves 1997). Thus we also measured spectral absorbance values between 200 and 800 nm. A Shimadzu UV-1650PC UV-Visible Spectrophotometer was used to measure spectral absorbance between 200 and 800 nm. Distilled water absorbance values were subtracted from the absorbance scans. Three bottles from each lake were collected; DOC concentration and absorbance data presented represents the mean

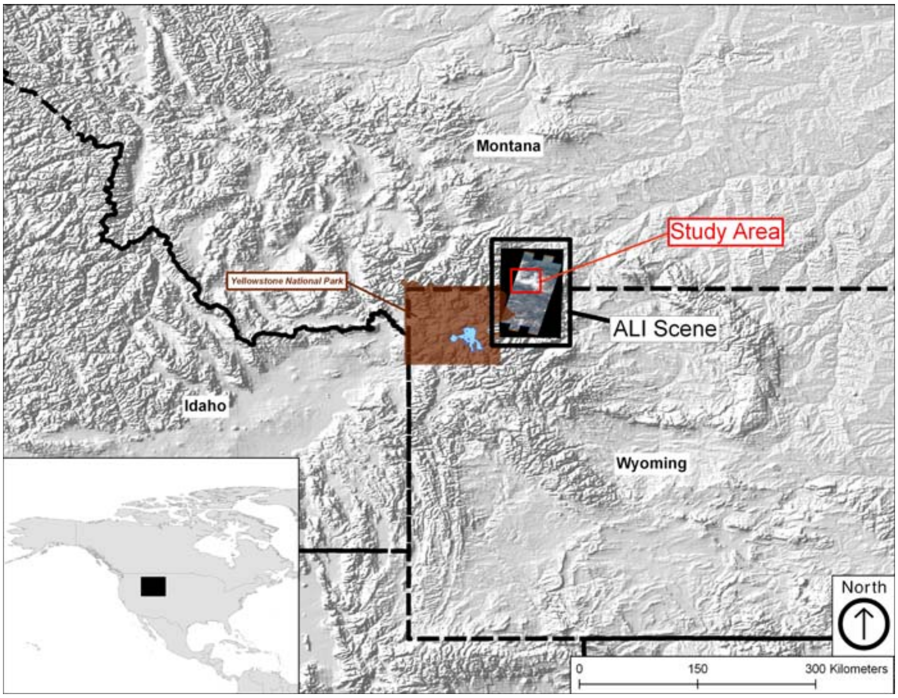


Fig. 1 Our study area lies within the Absaroka-Beartooth Wilderness on the border of Montana and Wyoming, USA northeast of Yellowstone National Park. The indicated Advanced Land Imager (*ALI*) Scene identifies the area within the ALI image captured on July 2, 2007. The digital elevation model (*DEM*) displayed in the background provides an idea of the topographic ruggedness of the landscape

value of the three bottles. Final analyses of the 20 lake samples identified obvious contamination of the Ouzel Lake sample, which was removed from the set resulting in 19 lakes being used in this study.

ALI reflectance model

We obtained ALI data from the USGS EROS data center comprising an image captured July 2, 2007 at 17:48 Greenwich Mean Time (10:48 Mountain Standard Time) with 0% cloud cover over the study area. These data were converted to reflectance values and adjusted for atmospheric effects. In sampling lake water color we adjusted for shoreline and bottom reflectance error by extracting pixels within NHD lake boundaries and removing the outermost bordering pixels. The 30 m ALI spatial resolution became an issue in four lakes with insufficient area beyond shoreline pixels and these were eliminated in this process reducing the observed dataset to 15 lakes.

Water color reflectance is best detected by blue light wavelengths (~400–500 nm) but, when sensed by satellite sources, blue light is subject to greater atmospheric absorption and scattering than other bandwidths (Jensen 2005; Kutser et al. 2005a, b). Other researchers have used band normalization ratios to normalize reflectance values and reduce atmospheric effects. For example, Kutser et al. (2005a, b) use a band 2 (525–605 nm)/band 3 (630–690 nm) ratio as a predictor of lake water color. Unfortunately, the green and red bands of our ALI image showed scanning errors in some of the lakes and we could not use band combinations. Further, other reflectance errors existed within lake boundaries in the blue band and appear to be due to shadowing or reflection in areas of high topographic relief. These spikes in the data were avoided by calculating minimum blue band reflectance values within the 15 training lakes. Final values were regressed against DOC concentration measurements and field sample spectral absorbance at wavelengths of 320, 420, 440, and 720 nm.

GIS watershed model

Watershed delineation

We delineated watersheds for study area lakes using ArcHydro Tools, an ESRI ArcGIS extension, and a USGS 1/3 arcsec (10 m) National Elevation Dataset digital elevation model (DEM). For this research, all NHD lakes within the study area (>2,000) boundary were input for watershed delineation using the 10 m DEM. The result was 460 output watersheds from the original >2,000 NHD lakes. The failure to produce adequate watersheds in most lakes likely derives from the DEM detail in relation to watershed size and shape. Further quality assessment of output watersheds resulted in 353 usable watersheds. Criteria for removal through quality assessment included sites where watersheds were smaller than lakes and/or obviously misshapen caused by errors within the DEM.

Land cover

Fixation of carbon to soils depends on vegetation cover, type, and location (Bukaveckas and Robbins-Forbes 2000; Frost et al. 2006; Johnson et al. 2006; Rae et al. 2001). Publicly available digital land cover data were insufficient for our specific research needs and we created a land cover map from the obtained ALI data for use within our GIS model. The map was created using an unsupervised classification of a principal components analysis (PCA). The PCA involved all ALI bands and multiple vegetation indices. The output grid included 30 identified classes. These were identified for land cover type using color aerial photography with 1 m spatial resolution and compiled into seven classes: water, ice/snow, rock, forest, shrubland, grassland, and wetland. Our independent accuracy assessment of this land cover map revealed an overall classification accuracy of 72.27%.

We further reclassified our land cover by focusing on the importance of carbon fixation. We combined areas with rock or ice assumed not to play an important role in DOC production. Areas with vegetation were also combined into one class defining areas of DOC production. This combination reduced statistical multiple collinearity within the small sample dataset and the reduction of classes better represents the study area where watersheds display a contrasting relationship of vegetation versus no vegetation.

Hydrologic DOC enhancement

Hydrologic processes, as functions of watershed geomorphology, control how much and how often stored carbon is exported from soils. Snowmelt-dominated watersheds, for example, depend on increased runoff produced asynchronously for the movement of DOC from terrestrial sources to downstream sites (Boyer et al. 1997, 2000). Ultimately, the intensity of runoff events induced by snowmelt and precipitation determines export to downstream sites (Boyer et al. 1997, 2000; Cooper et al. 2007; Inamdar et al. 2004; Pace and Cole 2002; Striegl et al. 2005; Worrall et al. 2002). In this study, field sampling occurred in July 2007 and, therefore, avoided peak snowmelt times in early summer where major variation in runoff would have occurred. For this model, we assume runoff is synchronous throughout the study area.

Wetlands are critical in enhancing downstream DOC concentrations (Bukaveckas and Robbins-Forbes 2000; Creed et al. 2003; David and Vance 1991; Freeman et al. 2001; Worrall et al. 2002). In addition to wetlands with standing water or hydric vegetation, topographic characterization identifies subsurface sites of hydrologic importance to DOC export (Creed et al. 2003; Ogawa et al. 2006). Available wetland data for the Absaroka-Beartooth Wilderness region, then, are incomplete in identifying sites of DOC enhancement. The 1:24000 National Hydrography Dataset (NHD) wetlands are drawn from aerial photography whereas the National Land Cover Dataset (NLCD) is based on Landsat satellite imagery. Additional wetland data from the National Wetlands Inventory (NWI) are not available within the Absaroka-Beartooth Wilderness region. Commonly, the available datasets are insufficient in identifying wetlands beneath the canopy and, most important, insufficient in identifying subsurface sites of DOC export.

We use topographic characterization of a digital elevation model in order to address hydrologic DOC enhancement. We calculated proportionate slope data for the study area using the same 10 m DEM obtained for watershed delineation. We determined optimal DOC enhancement zones by calculating median percent slope values from the 10 m DEM within the NHD wetlands resulting in 5% median slope. We further limited low slope areas (<5%) by vegetation cover, removing areas with low slope coinciding with rock or perennial ice/snow cover from the low slope grid. Rock outcroppings and perennial snow/ice have little or no soil structure beneath and, therefore, are incapable of storing substantial amounts of DOC for future export regardless of slope. In addition, it is known that proximity of wetlands to downstream lakes increases DOC export to the lakes (Boyer et al. 1997; Canham et al. 2004; Williamson and Zagarese 2003). We calculated 0–5% slope area within lake watersheds at various distances to lakes and found that the best predictor of DOC concentration used the areal proportion of 0–5% slope in the entire watershed. Final analyses involved the linear regression of proportionate 0–5% slope areas within lake watersheds against lake DOC concentrations.

Complete GIS model

The predictive DOC model uses multiple regression of proportionate lake watershed vegetation and area with 0–5% vegetated slope within watersheds against 19 field-measured lake DOC concentrations. In addition, we regressed these landscape variables against spectral absorbance at 320 nm (Williamson et al. 1999), 420 nm (Kutser et al. 2005a, b), 440 nm (Cuthbert and del Giorgio 1992), and 720 nm as a control group to identify any influence of our measured watershed variables on water color. Finally, we used the regression trend of the GIS watershed model to predict DOC concentrations in 353 lakes, determined from 353 DEM-delineated watersheds, because this relationship was sufficient for extrapolation.

Results

Regression analyses of the two independent models involved in this research provided different predictive strengths. The GIS watershed model resulted in a high R^2 value with the two watershed inputs (proportion vegetation and proportion 0–5% slope), whereas the ALI reflectance model resulted in a lower R^2 value and was further limited by only 15 model inputs. Though the models displayed different predictive strengths, their results are consistent.

ALI reflectance model

ALI blue band values show a generally weak relationships with both DOC concentration and spectral absorbance of the sampled dataset. The strongest relationship exists between blue band minimum reflectance values and DOC concentration (Table 1). Spectral absorbance measurements showed the best relationship with reflectance values in the blue wavelengths (420 and 440 nm), as expected. What was not expected was that DOC concentrations provided a slightly stronger relationship with reflectance values than spectral absorbance (Table 1). Ultimately, both ALI reflectance models lack predictive power due to the small number of training samples.

GIS watershed model

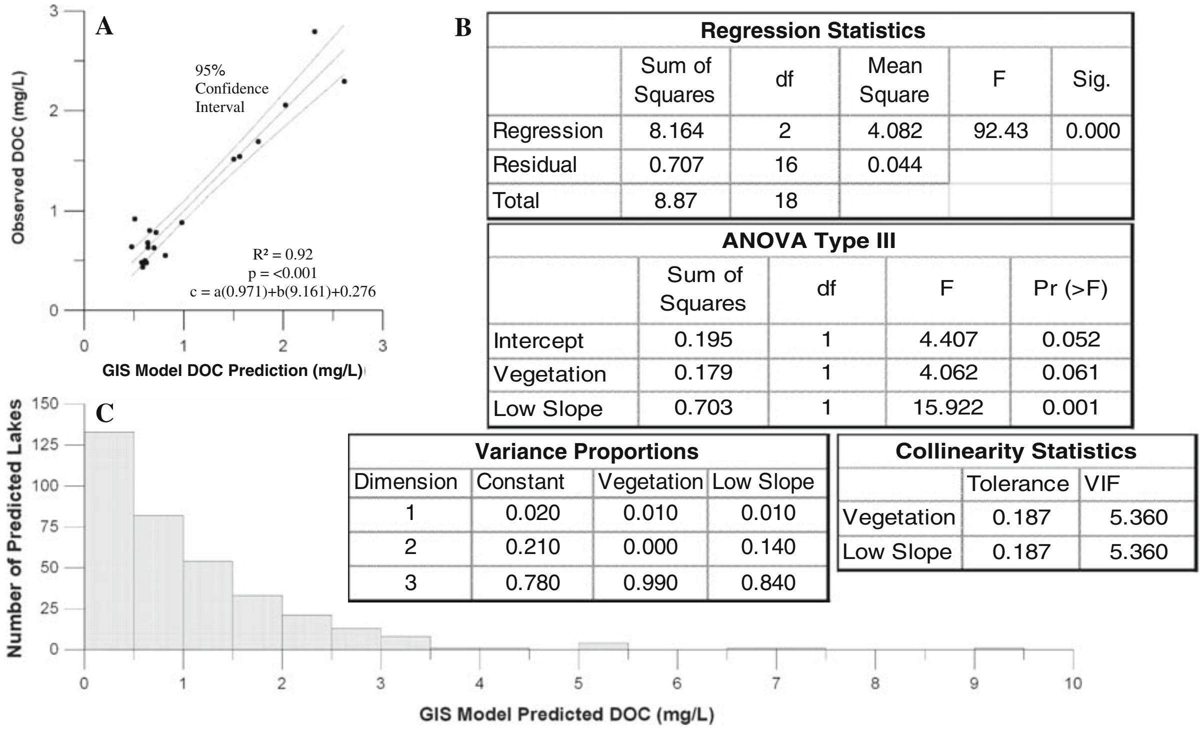
Watershed vegetation (identified using unsupervised classification of ALI data) and 0–5% slope areas (identified using a 10 m resolution DEM) provided a very good relationship with spectral absorbance at shorter wavelengths (320, 420, and 440 nm; Table 2) and DOC (Fig. 2). The strength of the relationship between spectral absorbance and watershed variables decreases with increasing wavelength (Table 2). The varying strengths of these relationships may simply be due to the strong correlation of DOC with spectral absorbance as watershed variables best relate to DOC

Table 2 Regression results of two GIS watershed model variables against a range of spectral absorbance values

	Variable	Slope	*Y*-intercept	R^2	*P*
ALI-vegetation	λ320	0.371	0.013	0.879	<0.001
	λ420	0.074	0.038	0.812	<0.001
	λ440	0.055	0.039	0.782	<0.001
	λ720	0.004	0.088	0.174	0.075
0–5% Slope	λ320	1.769	0.095	0.879	<0.001
	λ420	0.360	0.054	0.848	<0.001
	λ440	0.268	0.050	0.827	<0.001
	λ720	0.020	0.088	0.236	0.035

Table 1 Regression results of ALI blue band minimum reflectance values against the Log transform of DOC and a range of spectral absorbance values

	Variable	Slope	*Y*-intercept	R^2	*P*
ALI minimum blue band reflectance	Log DOC (mg/l)	−21.097	3.309	0.725	<0.001
	λ320	−6.029	1.129	0.480	0.005
	λ420	−1.358	0.285	0.550	<0.001
	λ440	−1.032	0.226	0.549	<0.001
	λ720	−0.090	0.104	0.195	0.099



Regression Statistics					
	Sum of Squares	df	Mean Square	F	Sig.
Regression	8.164	2	4.082	92.43	0.000
Residual	0.707	16	0.044		
Total	8.87	18			

ANOVA Type III				
	Sum of Squares	df	F	Pr (>F)
Intercept	0.195	1	4.407	0.052
Vegetation	0.179	1	4.062	0.061
Low Slope	0.703	1	15.922	0.001

Variance Proportions			
Dimension	Constant	Vegetation	Low Slope
1	0.020	0.010	0.010
2	0.210	0.000	0.140
3	0.780	0.990	0.840

Collinearity Statistics		
	Tolerance	VIF
Vegetation	0.187	5.360
Low Slope	0.187	5.360

Fig. 2 **a** Relation between predicted and observed DOC concentrations using the GIS model including proportionate vegetated area (*a*) and proportionate area of 0–5% slope (*b*) within study lake watersheds ($R^2 = 0.92$). **b** Resulting statistics from the regression showing interaction between the independent variables. Interaction is expected as wetlands that generate DOC are typically vegetated. Extrapolation of this model to 353 study area lakes results in a range of DOC concentrations mostly within the range of the training dataset (**c**)

Table 3 Regression results of DOC concentrations against a range of spectral absorbance values

	Variable	Slope	*Y*-intercept	R^2	*P*
DOC (mg/l)	λ320	0.132	0.029	0.949	<0.001
	λ420	0.026	0.041	0.886	<0.001
	λ440	0.020	0.041	0.864	<0.001
	λ720	0.002	0.088	0.281	0.020

concentrations (Table 3). Therefore, model predictions used for comparison only include DOC concentrations. Collinearity statistics of the complete DOC model, concerning two input variables, result in a variance inflation factor of 5.360.

Discussion/conclusion

Both the ALI reflectance model and the GIS watershed model are effective in predicting DOC concentrations and select spectral absorbance values in the study lakes. These models, however, are limited by small training datasets. The ALI reflectance model showed the weakest relationship and had a reduced training dataset (15) due to ALI pixel size whereas the GIS watershed model provided the best relationship and was able to retain the original training dataset (19).

The strong relationship between spectral absorbance values at shorter wavelengths (320–440 nm) and DOC indicates that DOC quality did not show any strong variation among lakes in the study region, and thus photobleaching did not introduce error in our research. Additionally, spectral absorbance values at shorter wavelengths correlated highly to the GIS watershed model. Shorter wavelengths are not often considered but may be highly important in alpine lakes where both incident solar UV and water transparency to UV radiation are often high. Watershed variables do appear to have some control over water transparency. ALI spectral data correlated most highly within blue wavelength spectral absorbance values (420 and 440 nm). This may derive from using the blue ALI band (450–515 nm) where spectral values were within a similar range.

Our GIS watershed model shows that the strongly contrasting landscape of subalpine and alpine environments provides optimal conditions for identifying watershed variables that influence DOC in lakes via simple and broad classes: vegetation presence or absence and 0–5% slope. Land cover as vegetated or unvegetated classes correlates well with lake DOC concentrations and may be attributed to the strongly contrasting land cover within subalpine and alpine lake watersheds. However, ALI-derived land cover shows that vegetation, especially late-successional forest cover, is not well represented throughout all study area watersheds. Extrapolation of 353 lakes near the 19 study lakes showed a cluster of DOC concentration values below that the lower limit represented in the training dataset. Fifty-five of these 353 study area lakes watersheds had no identified vegetation within their watersheds. These lakes are expected to have extremely low DOC concentrations compared to those within the training dataset, but may also differ from each other in autochthonous DOC production. Autochthonous DOC influence is immeasurable with our independent variables and these slight differences, located within the *Y*-intercept = 0.276 mg/l, would be outside of the broader scope of this research project. Flat areas (0–5% slope) in watersheds provided a better relationship with lake DOC concentrations than vegetation. Field study would be necessary to determine the specific hydrologic function of identified 0–5% slope sites (i.e., canopy-hidden wetlands or subsurface wetlands). Compared to similar work by Canham et al. (2004) in lower elevation systems, our GIS watershed model, dealing specifically with subalpine and alpine environments, provides a higher R^2 value.

Compared to the GIS watershed model the ALI reflectance model had greater limitations. The greatest limiting factor in developing the ALI reflectance model was the image spatial resolution in relation to lake size and shape in the study area. Pixel size relative to lake area led to the loss of four sampled lakes. Additionally, environmental factors produced error within some lake pixels requiring the use of minimum reflectance values. Finally, scanning errors in most ALI bands prevented us from using multiple pixels in individual lakes and band normalization ratios that would allow us to compare other images. In this study area, with particularly high topographic relief and small lakes, a finer-scaled remote sensing data source would have been more effective in measuring DOC and spectral absorbance at the landscape scale but might still be hindered by difficulties associated with remote sensing in high-relief landscapes.

Our GIS watershed model showed the most promise of the two DOC models. Potential improvements include a more detailed and spatially explicit model in order to explain more variation in DOC concentrations among Absaroka-Beartooth Wilderness Lakes. For example, the sampled lakes with the two highest DOC concentrations have substantially different watersheds and both lakes vary similarly on opposite sides of the trend (Fig. 2c). Kersey Lake has ~50% of its watershed covered in woody vegetation and is predicted low by the GIS model while the Chain Lakes are mostly grassland and predicted high within the GIS model. This is consistent with previous research on differences in lake transparency as a function of grasslands versus forests (Rae et al. 2001). Therefore, a more detailed model of Absaroka-Beartooth Wilderness lakes should include a comparison of vegetation type within low slope areas that would identify the makeup of the wetland. A spatially explicit model may also benefit from finer-resolution spatial data. In some cases, lake watersheds were represented by less than 100 30 m × 30 m pixels. Though this contrasting landscape lends well to simple DOC modeling, higher-resolution spatial data and more physically sampled lakes with late successional vegetation are necessary for a more complete representation.

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