Supplementary Information for
Enhanced greenhouse gas emission from exposed sediments along a hydroelectric reservoir during an extreme drought event

Hyojin Jin†, Tae Kyung Yoon†, Seung-Hoon Lee2, Hojeong Kang2, Jungho Im3, Ji-Hyung Park†

1Department of Environmental Science and Engineering, Ewha Womans University, Seoul 120-750, Republic of Korea

2School of Civil and Environmental Engineering, Yonsei University, Seoul 120-749, Republic of Korea

3School of Urban and Environmental Engineering, Ulsan National Institute of Science and Technology, Ulsan 689-798, Republic of Korea

†These authors contributed equally.

*Corresponding author: Ji-Hyung Park (jhp@ewha.ac.kr)

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Study site

Lake Soyang is the deepest and largest reservoir in South Korea (37°56′44″N, 127°48′52″E; Figure 1) with a maximum depth of 110 m near the dam and a total watershed area of 2,700 km² [Lee et al., 2013]. The reservoir has a dendritic shape, consisting of the primary axis that is 60 km long and 0.5 km wide and many lateral branches. Approximately 87% of the watershed is covered with forests, whereas agriculture and urban residential areas represent 6% and 7%, respectively. The reservoir is oligo-mesotrophic, with relatively small inputs of domestic and industrial wastewater, but agricultural runoff from expanding croplands on the steep mountainous terrain has been increasing in recent decades [Park et al., 2010; Lee et al., 2013].

Field measurements of reservoir $pCO_2$ and $CO_2$ efflux

Continuous measurements of water $pCO_2$, water temperature and light intensity at 1-min intervals were conducted at 20 cm below the surface of the reservoir near the dam from June 8 through June 22, 2015 (Figure 1). The atmospheric $pCO_2$ was not measured at the study site, so we used concurrent measurements from a downstream (~150 km) river site. The atmospheric $pCO_2$ was measured at the height of 1 m above the river surface [Yoon et al., 2016]. The $pCO_2$ was measured by a diffusion-type, non-dispersive infrared (NDIR) CO$_2$ sensor (GMT222, Vaisala, Finland) enclosed in a water impermeable, gas permeable polytetrafluoroethylene (PTFE) membrane tubing (International Polymer Engineering, USA) [Johnson et al., 2010]. The accuracy of CO$_2$ sensors was
checked with CO₂ standard gases of known concentrations in the laboratory before and after
deployment. The outputs of the membrane-enclosed sensor were corrected by measured water
temperature and barometric pressure (Johnson et al., 2010). The efflux of CO₂ from the reservoir
surface was calculated using differences in pCO₂ between the lake surface water and the
atmosphere (measured at the downstream river site) and an estimated gas transfer velocity
[Raymond et al., 2013]. Raymond et al. [2013] used published relationships between lake area and
Schmidt number of 600 (k₆₀₀) to derive 1.90 m d⁻¹ as a mean k₆₀₀ for large lakes >10 km². The same
k₆₀₀ value was used in our CO₂ efflux calculation based on the size of the Lake Soyang.

On the day in which the two-week monitoring of pCO₂ near the dam was completed, CO₂ efflux
were measured along a 200-m transect in an upper reach of the main reservoir channel, 36 km
upstream of the dam (Figure 1). The upper reaches of the main and lateral branches of the reservoir
were severely affected by droughts, exposing bottom sediments along shallow water channels
(Figure 1). Although the studied segment of the reservoir has a mean depth exceeding 1 m under
usual flooding conditions, at the time of field study the inflowing water channel had become very
shallow (<0.5 m) and narrow (<50 m), exposing large areas of sediment (> 200 m wide) on the side
in which the study was conducted. The rates of CO₂ efflux from the water surface of flooded
sediment along the margin of water channel (sampling points A and B) and exposed sediments (C,
D, E and F) were determined by using a metallic, flow-through soil gas flux chamber with an inner
diameter of 9.5 cm and a height of 16.5 cm, connected to a CO₂ analyzer (LI 820, LI-COR, USA).
Sampling point C, which was closest to the water channel, and its adjacent point D represented areas of recently exposed sediments with little vegetation cover, whereas various species of grass were established near points E and F, with vegetation density increasing toward point F. The gas flux chamber was placed on top of a metallic ring that had been gently pushed approximately 1 cm into the sediment. The rate of CO$_2$ efflux from the sediment surface, or the bare surface with no vegetation at points E and F, was determined by measuring the increases in CO$_2$ concentration inside the closed dark chamber after the headspace concentration had been scrubbed to below an ambient level. Although CO$_2$ measurements lasted for 5 min, the average increase in CO$_2$ concentration over a period of approximately 1 min showing linear concentration increase was converted to the amount of CO$_2$ emitted from the unit area per day (mg C m$^{-2}$ d$^{-1}$) based on the ideal gas law and the ratio of the chamber volume to the surface area [Holland et al., 1999]. At the flooded sediment along the edge of the sediment bank (point B), the chamber was also placed on top of the metallic ring that had been pushed into the bottom sediment. In the rapidly flowing water < 50 cm deep (point A), 80 cm from the edge of the sediment bank, the bottom 1 cm of the chamber was immersed in water by using a support column. At each of the six transect locations, three replicate measurements were conducted along a line perpendicular to the transect at a minimum distance of 1 m from each replicate measurement point. CO$_2$ concentrations, air temperature and pressure were measured inside the chamber at 1-s intervals for approximately 5 min.

Laboratory incubation and analyses
Surface sediment samples (~10 cm) were collected by using a metal corer (inner diameter: 10 cm; depth: 10 cm) from the same locations in which the CO$_2$ efflux was measured. Samples were immediately transported to the laboratory and a portion of each sediment sample was frozen for real-time polymerase chain reaction (PCR) analysis with no prior treatment. Any live plant roots and microfauna present were removed from the remaining samples by using forceps. Each remaining sample was homogenized and a portion of this homogenized sample was oven-dried at 60°C for 48 h to determine gravimetric soil water content by measuring the ratio of weight loss from drying against the dry weight.

To measure production potentials of three major GHGs – CO$_2$, CH$_4$ and N$_2$O, approximately 20 g of fresh sample was placed in 120 ml vials and the vials were then sealed with gas-impermeable butyl septa and aluminum crimps (Wheaton, USA) and incubated at 20°C for 48 h. To simulate field conditions, the bottom sediment from the flowing water location (point A) was overlain by 20 ml of the water collected from the same location. The gas concentrations in the headspace air samples collected at 0, 24 and 48 h were measured by using a gas chromatograph (7890A, Agilent, USA) fitted with a Supelco Hayesep Q 12 ft 1/8” column. The samples from point A contained both sediment and water, so the incubation bottles were vigorously shaken for 2 min before each headspace gas sampling to equilibrate gas concentrations between the headspace air and the sediment-water mixture. Unlike the other sediment samples, we expected that gas concentration changes in the headspace air of the samples from point A would represent the net production or
consumption of GHGs in the sediment-water mixture. After confirming that all three-point measurements showed linear increases, the increase in gas concentration over the 48-h incubation period was converted to the amount of each gas produced from a unit area of 10 cm deep sediment based on the ideal gas law and the ratio of soil mass to the area of the sediment corer [Holland et al., 1999].

The activity of four representative soil enzymes including phenol oxidase, β-glucosidase, N-acetyl glucosamidase and phosphadase was determined with sieved and homogenized surface (10 cm) sediment samples within two days from the sampling. Although oxygenation of surface sediment might have differed across the sampling transect, our measurements of enzyme activity in the bulk sediment of 10 cm depth would represent an average condition prevailing in the surface sediment of each sampling location. L-DOPA was used to measure the phenol oxidase, whereas methylumbelliferyl (MUF)-β-D-glucopyranoside (MUF-G), MUF-N-acetyl-β-D-glucosaminide (MUF-N) and MUF-phosphate disodium salt (MUF-P) were used as model substrates for β-glucosidase, β-N-acetylglucosaminidase (NAGs) and phosphatase, respectively [Kang and Freeman, 1999].

The copy numbers of bacterial 16S ribosomal RNA (16S rRNA) genes were measured to estimate the bacterial abundance in the soil. DNA was isolated by using the UltraClean Soil DNA Isolation Kit (MoBio Laboratories, USA) on 1 g of the frozen soil sample. Bacterial DNA molecules were amplified by using an I-CyclerTM (Version 3.0a, Bio-Rad, USA) and SYBR Green for the
detection system (Bio-Rad). Each reaction in 20 μl sample contained a specific primer set for
bacteria including 341F: 5′-CCTACGGGAGGCAGCAG-3′ and 797R: 5′-
GGACTACCAGGGTCTAATCCTGTT-3′ [Lane, 1991; Nadkarni et al., 2002]. The amplification
followed a three-step PCR that included 40 cycles with denaturation at 95°C for 25 s, primer
annealing at 64.5°C for 25 s and extension at 72°C for 25 s. A standard curve was created by using
a 10-fold dilution series of plasmids containing the bacterial 16S rRNA gene from the samples.

**Estimating drought-exposed sediment areas using remote sensing data**

A total of 16 Landsat 7 (L7) Enhanced Thematic Mapper plus (ETM+) and Landsat 8 (L8)
Operational Land Imager (OLI) satellite data were used to estimate the changes in water surface
areas over the reservoir from July 2013 to August 2015. The data were downloaded from the United
States Geological Survey (USGS) website at glovis.usgs.gov. Both types of data were
atmospherically corrected by using Exelis Visual Information Solutions (ENVI) Fast Line-of-sight
Atmospheric Analysis of Hypercubes (FLAASH) algorithm to produce reflectance. Data-void
pixels in L7 data due to the well-known scan line corrector (SLC)-off problem were corrected by
using a gap filling approach. By using atmospherically corrected reflectance, the Normalized
Difference Water Index (NDWI) was computed as \((\rho_G - \rho_{NIR})/(\rho_G + \rho_{NIR})\), where \(\rho_G\) is the
reflectance measured at the green wavelength at 525–605 nm for L7 and 525–600 nm for L8, and
\(\rho_{NIR}\) is the reflectance at the near-infrared wavelength at 750–900 nm for L7 and 845–885 nm for
L8. Clouds, snow and ice in the scenes were removed by using Landsat 7 and 8 Fmask data. To
identify water areas, Otsu’s method was applied, which is a commonly used image threshold-based
segmentation approach based on the assumption of a bi-modal histogram with two classes (i.e.,
water vs. non-water) [Li et al., 2013; Du et al., 2014; Rokni et al., 2014]. Binary water area maps
produced from the 16 Landsat images using the approach mentioned above and temporal variations
of the delineated water areas are depicted in Figure S1 in the supporting information.
Figure S1. Binary water area maps produced from the 16 Landsat images (top) and changes in delineated water areas from July 7, 2013, to August 6, 2013 (bottom). When the regression between the reservoir water level data and the reservoir surface area estimates obtained from remote sensing data ($R^2 = 0.84$, $n = 17$, $P < 0.001$) was used to estimate changes in the reservoir surface area during the 151 emergency status days, the reduced reservoir surface area relative to the previous peak water level on July 7, 2013, was on average 11.9 km$^2$ (9.9–14.6 km$^2$).
Figure S2. Cluster analysis of bacterial, fungal and archaeal community structures determined by t-RFLP analysis.
References


surface water mapping using the normalized difference water index from TM, ETM+ and ALI, Remote Sensing, 5, 5530–5549.


