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Forsmark site investigation

Distribution, biomass, production and respiration of submerged vegetation in Lake Bolundsfjärden

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October 2006

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Keywords: Biomass, Primary production, Respiration, Lake Bolundsfjärden, Submerged vegetation, *Chara, Najas,* AP PF 400-06-031.

Abstract

We have measured biomass and primary production of submerged vegetation in Lake Bolundsfjärden. Samplings were performed three times during the summer 2006. Stonewarts (*Chara sp*) dominated the biomass totally at all three occasions. In September *Najas marina* was also present in some samples.

The biomass varied over time and was highest in July (median 209 g dw m^{-2} compared to 81 and 51 g dw m^{-2} in June and September, respectively). These values are in the same order of magnitude as values from the same lake in 2004 and also from the nearby Lake Fiskarfjärden (2004). The median carbon content in summer samples (n=60) was 21 g $C \cdot m^{-2}$. Extrapolation of results from the summer samples to the whole lake area results in a total biomass of 15,700 kg dw (4,200 kg C).

The primary production did also vary over time. The highest production per unit dry weight was found in June (1.3 mg O_2 g dw^{-1} h^{-1}) and lowest in September (0.7 mg O_2 g dw^{-1} h^{-1}). The same was true for the respiration (0.6 mg O_2 g dw^{-1} h^{-1} in June and 0.2 mg O_2 g dw^{-1} h^{-1} in September). However, the estimated production per unit solar energy is totally different; the highest production value was found in September (0.0028 mg O_2 g dw^{-1} kJ^{-1} m^2), whereas the values for June and July were lower (0.0005/0.0007 mg O_2 g dw^{-1} kJ^{-1} m^2). The production per unit area was highest in July (222 mg O_2 m^{-2} h^{-1}, compared to 108 and 33 mg O_2 m^{-2} h^{-1} in June and September, respectively), which is expected since the biomass was very high at that time. Compared to other studies, our production values are within the same range; some values are much higher than ours, but there are also lower values. When calculating annual production the figures vary according to the data set used. Using the values we find most confidence in results in an annual production of about 344 g O_2 m^{-2} y^{-1} or 108 g C m^{-2} y^{-1}.

The results from the investigations are associated with a number of uncertainties. However, we suggest that the large number of replicates, and the accordance with other studies, implies that the results are of good quality and may be used for modelling of the ecosystems in Lake Bolundsfjärden, as well as other similar lakes in the same area.

Sammanfattning

Vi har mätt biomassa och produktion av undervattensvegetation i sjön Bolundsfjärden tre gånger under sommaren 2006. Kransalger (*Chara sp*) var helt dominerande vid alla tre tillfällena. I september fanns *Najas marina* i några av proven. Biomassan varierade över tiden och var högst i juli (medianvärde 209 g torrvikt m^{-2} jämfört med 81 respektive 51 g torrvikt m^{-2} i juni och september). Dessa värden är i samma storleksordning som värden från Bolundsfjärden 2004 och från den närbelägna sjön Fiskarfjärden (2004). Medianvärdet av kolbiomassan för hela sommaren var 21 g kol m^{-2}. Räknar man upp biomassan av undervattensvegetation för hela sjön får man en total biomassa på 15 700 kg torrvikt eller 4 200 kg kol.

Primärproduktionen varierade också över tiden. Högst värde per biomassa uppmättes i juni (1,3 mg O_2 g torrvikt^{-1} timme^{-1}) och lägst i september (0,7 mg O_2 g torrvikt^{-1} timme^{-1}). Samma trend gäller även respirationen (0,6 mg O_2 g torrvikt^{-1} timme^{-1} i juni och 0,2 mg O_2 g torrvikt^{-1} timme^{-1} i september). Tittar man på produktionen per solinstrålningsenhet är bilden dock en helt annan; högst produktionsvärden fanns i september (0,0028 mg O_2 g torrvikt^{-1} kJ^{-1} m^2) medan produktionsvärdena för juni och juli är ungefär lika (0,0005/0,0007 mg O_2 g torrvikt^{-1} kJ^{-1} m^2). Produktionen per area var högst i juli (222 mg O_2 m^{-2} timme^{-1}, jämfört med 108 och 33 mg O_2 m^{-2} timme^{-1} i juni och september), vilket var förväntat eftersom biomassan var mycket hög då. Jämfört med andra studier ligger våra värden inom samma intervall; några värden är mycket högre än våra, men det finns även lägre värden. När man räknar om värdena till årlig produktion varierar resultatet beroende på vilka underlagsdata man väljer att använda. Den årliga produktionen av undervattensvegetation i Bolundsfjärden, beräknad utifrån de värden som vi bedömer är mest realistiska uppskattas till 344 g O_2 m^{-2} år^{-1} eller 108 g kol m^{-2} år^{-1}.

Reslutaten från denna undersökning är förknippad med en rad osäkerheter. Det stora antalet replikat, samt överensstämmelsen med andra studier, gör dock att vi bedömer att våra data har god kvalitet och kan användas för modellering av ekosystemen i Bolundsfjärden, liksom för andra liknande sjöar i samma område.

Contents

1 Introduction

This document reports the results gained by the measurements of submerged vegetation (mainly *Chara sp*, herafter called *Chara*) in Lake Bolundsfjärden during the summer 2006. The investigation is one of the activities performed within the site investigation at Forsmark. The work was carried out in accordance with activity plan AP PF 400-06-031 (Table 1-1). Activity plans are SKB's internal controlling documents. The original results are stored in the primary database SICADA and are traceable by the activity number.

The lakes in the Forsmark site investigation area are characterised as oligotrophic hardwater lakes. Large areas of the benthic habitat in these lakes are covered by the macroalgae *Chara* /Brunberg et al. 2004, Huononen 2005/. An investigation of the biomass of aquatic vegetation in Lake Bolundsfjärden has been performed previously /Huononen 2005/. That study was performed at one occasion with few replicates, and the biomass estimates showed a high variation. Thus, further studies are needed to accurately determine the biomass of submerged vegetation.

An ecosystem budget performed for the adjacent Lake Eckarfjärden in Forsmark /Andersson and Kumblad 2006/ showed that *Chara* plays a significant role in the lake metabolism. *Chara* was one of the main primary producers in the lake. However, their results were based on literature values, as no production measurements from the lake were available. In 2005, production of *Chara* in Lake Bolundsfjärden was measured at one occasion /Karlsson 2006/, but the variance was high also in this study and additional data are needed to get reliable estimates of yearly production of *Chara*.

In this study, we have measured biomass, production and respiration of submerged vegetation (mainly *Chara*) in Lake Bolundsfjärden (Figure 1-1). The biomass was measured in June, July and September 2006, with 20 replicates at each occasion (see map in Figure 1-1). The production and respiration were estimated by O_2 incubations at the same occasions as the biomass investigations. The distribution of *Chara* along the shores of the lake was investigated in the beginning of the growing season.

Table 1-1. Controlling documents for performance of the activity.

Activity plan	Number	Version
Mätning av produktion och respiration i Bolundsfjärden 2006	AP PF 400-06-031	1.0

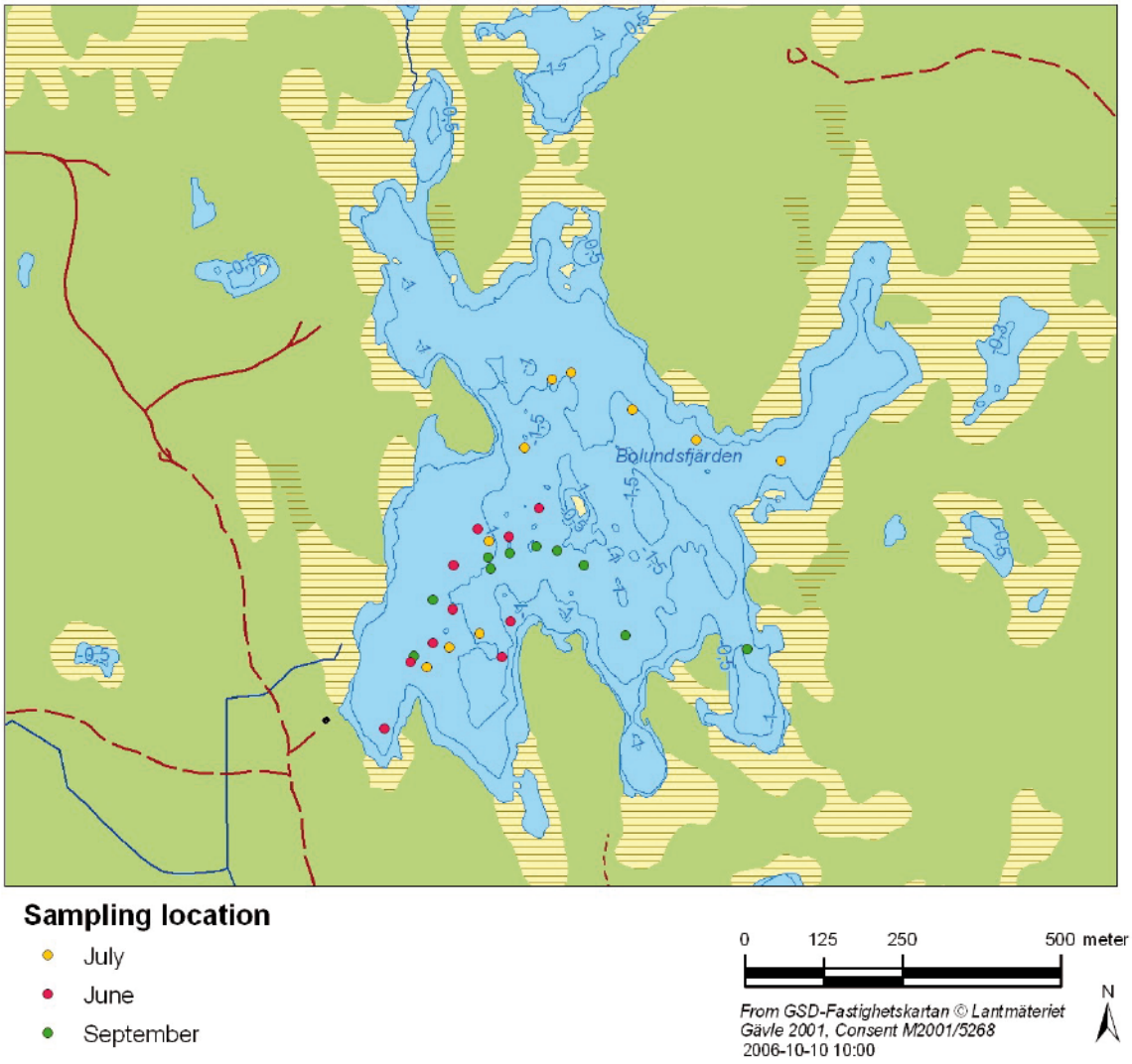

Figure 1-1. *Locations for biomass sampling in Lake Bolundsfjärden (two replicates were sampled at each location).*

2 Objective

The objectives of this study were to measure the biomass, production, respiration and distribution of submerged vegetation (mainly the macroalgae *Chara*) in Lake Bolundsfjärden. The biomass and production of submerged vegetation are essential information for modelling of the lake ecosystems in the area.

3 Equipment

3.1 Description of equipment

3.1.1 Biomass

A GPS was used to determine the point position of the sampling locations (precision about ± 15 m) and a depth gauge was used to determine the sample depth. Divers equipped with an iron frame (0.2 m×0.2 m) with an attached net bag (see Figure 3-1) sampled submerged vegetation from the benthic habitat. The wet biomass was measured on a balance with an accuracy of (± 0.1 g). Drying of samples was performed in an oven (Raypa, 150 l) and the dry weight was measured with an accuracy of (± 0.1 mg).

3.1.2 Production and respiration

100 ml bottles, 60 ml syringes and filters (0.45 µm pore size) were used for production and respiration measurements. Aluminium foil was used to cover some of the glass bottles and thereby achieving dark bottles for respiration measurements. An oxygen probe (Hach Lange, LDO HQ10) was used to determine the oxygen concentration in the bottles. The accuracy of the probe was ± 0.1 mg l^{-1} for the interval 0–8 mg l^{-1} and ± 0.2 mg l^{-1} for the interval 8–20 mg l^{-1}.

3.1.3 Distribution

A GPS was used when visually determining the distribution of submerged vegetation by rowing along the boarder of the lake (precision about ± 15 m).

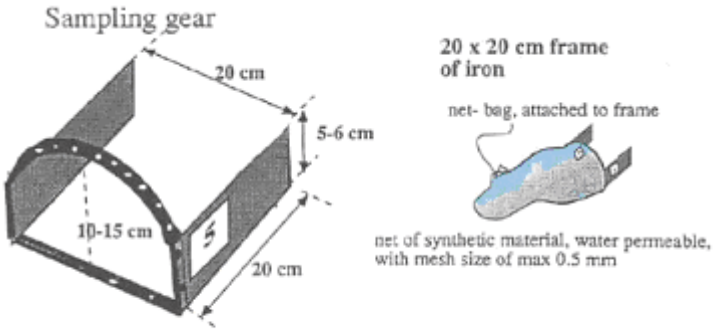

Figure 3-1. *Frames used when collecting submerged vegetation for biomass determinations. Modified original from Hans Kautsky, Dep. of Systems Ecology, Stockholm University.*

4 Execution

4.1 General

To investigate the biomass of submerged vegetation, samples from a known area were collected by divers in Lake Bolundsfjärden at three occasions in the summer of 2006. The distribution of submerged vegetation was investigated visually by rowing along the boarder of the lake (c 2–20 m from the shore depending on the navigability due to large rocks) in the beginning of the summer, noting areas with and without vegetation coverage.

To determine the production and respiration of the vegetation, small samples of submerged vegetation were incubated in glass bottles. During primary production, oxygen is produced and during respiration oxygen is consumed. By measuring the oxygen concentrations in glass bottles containing vegetation before and after incubation, the net primary production (gross production minus respiration) could be determined. Glass bottles covered with aluminium foil were used as dark bottles, and the difference in oxygen concentrations before and after incubation in the dark bottles provided the respiration of the submerged vegetation.

4.2 Preparations

Field protocols were copied on plastic papers for field notes.

Bottles used for primary production and respiration were marked in advance and a 1 m long string was tied to the bottles.

4.3 Execution of field work

4.3.1 Biomass

Biomass was measured on June 12, July 10 and September 6, 2006, with 20 replicates on each occasion. Two divers equipped with an iron frame (size 0.2×0.2 m) with an attached net (Figure 3-1) collected all submerged vegetation within the frame at randomly selected sites. The coordinates were registered at each location. At the first two occasions, water depth was recorded at each location. The vegetation samples were rinsed in a bucket to get rid of benthic microbiota and transferred to plastic bags and transported to the laboratory where wet weight was measured the same day. The samples were then kept in a freezer until they were dried at 60ºC to constant weight (approximately 2 weeks), and thereafter dry weight was measured.

4.3.2 Production and respiration

Production and respiration of submerged vegetation was measured on June 13, July 11 and September 7, 2006. *Chara* (and *Najas* in September) was collected and transported back to the shore in a covered bucket. Lake water was filtered through a 0.45 µm filter into 100 ml bottles. 5 light bottles and 5 dark bottles (covered with aluminium foil) were used (Figure 4-1). On July 11 and September 7, duplicate setups were used, with two different sets of glass bottles (for more details see Section 4.5).

The initial oxygen concentration in the bottles was measured with an oxygen probe. Thereafter, approximately 10–15 cm of *Chara*/*Najas* was added to each bottle. The bottles were sealed and kept dark until they were placed *in situ* at 0.9 m depth (average water depth of the lake).

Figure 4-1. *Bottles for measurement of primary production (left) and respiration (right).*

The bottles were incubated for approximately 4 hours (June 13: 10:15–13:45; July 11: 10:15–14:10; September 7: 10:20–14:20). When the incubations were stopped, the bottles were kept dark until the oxygen concentrations were measured. Both wet weight and dry weight of the incubated vegetation was measured.

4.3.3 Distribution

The distribution of submerged vegetation along the boarder of the lake was determined by visual inspection when rowing a boat. The coverage of vegetation was noted along the shore and when there was a boarder without vegetation coverage the width of this vegetation free area was noted and coordinates were identified with a GPS.

4.4 Data handling/post processing

4.4.1 Biomass

Carbon biomass (B_C) of submerged vegetation was calculated with the formula:

$B_C = B_{dw} \cdot 0.268$ /Hannu and Karlsson 2006/

where:

B_{dw} is the dry weight biomass

The total biomass of submerged vegetation in the lake was calculated by multiplying the median biomass per m^2 (all samples from the three different occasions) with the area of Littoral III in the lake (i.e. lake area excluding areas containing reed (Littoral I), cf /Brunberg et al. 2004/).

4.4.2 Production and respiraton measurements

Net primary production (NPP) and respiration (R) were calculated by the following formulas:

$$NPP = \frac{(O_2 lightbottle_{end} - O_2 lightbottle_{start}) \cdot V}{M \cdot T}$$

$$R = \frac{(O_2 darkbottle_{start} - O_2 darkbottle_{end}) \cdot V}{M \cdot T}$$

O_2 = oxygen concentration (mg l^{-1})

V = volume of the glass bottle (l)

M = biomass of Chara (g dw)

T = incubation time (h)

Using this formula, net primary production and respiration are expressed as mg O_2 g dw^{-1} h^{-1}. By multiplying the values per dry weight with the average biomass at that measurement occasion, the production or respiration per area can be achieved. For conversion to carbon production or respiration (mg C g dw^{-1} h^{-1}) a conversion factor of 0.3125 /Gutenstam 1979/ has been used.

The estimated primary production per hour was used to estimate daily primary production by assuming a direct proportionality to light /Wetzel and Likens 1991/. Light measurements were taken from Högmasten meteorological station, situated approximately 1.5 km from Lake Bolundsfjärden. The production per light unit (g O_2 J^{-1} h^1 m^2) on the sampling dates were assumed to be representative for longer time periods (Table 4-1), and to achieve yearly production these values were multiplied with total solar insolation during the whole period. During the period from October 1 to ice break the production was assumed to be negligible.

4.5 Nonconformities

In the production and respiration measurements, it was impossible to exclude all oxygen bubbles present in the glass bottle at the start of the incubation from the first set of glass bottles (type I) used on June 13. This may lead to underestimation of the primary production, as oxygen produced in the water can diffuse into the air bubble and thereby not be detected when measuring the dissolved oxygen concentration after incubation. In July and September a different set of glass bottles (type II) was used in addition to the original set. In the type II bottles, all air bubbles were possible to exclude, and compared to the type I bottles somewhat higher oxygen concentrations were measured (see Section 5.2). Thus, in the initial measurements, the production was most likely underestimated and the respiration was most likely overestimated.

Table 4-1. Time periods for which the measured production values were used when estimating annual production.

Sampling date	Used for period
June 13	Ice break – June 27
July 11	June 28 – August 9
September 7	August 9 – September 30

The problem with the type II bottles was that they had a too narrow neck for the oxygen probe. Oxygen concentration could therefore not be measured directly within each bottle. No individual start values were measured for these bottle, instead an average oxygen concentration value for the bottles of type I were used. After incubation, the water from the type II bottles was poured into another bottle before oxygen could be measured. The production by *Chara* and *Najas* resulted in highly oversaturated water with respect to dissolved oxygen. The pouring of water between bottles could potentially lead to that some of the produced oxygen was released to the air before measurements and thus result in underestimates of the production. However, since large oxygen production was noted, we assume the influence to be small. In conclusion, the production values given in this report involve some uncertainties. However, the results can be considered as good estimates for lakes in the Forsmark area, and these estimates are better to use than literature values from other lakes for further calculations in ecosystem models.

5 Results

The original results are stored in the primary database SICADA and are traceable by the activity number AP PF 400-06-031. The whole data set is presented in Appendices 1 and 2.

5.1 Biomass

The biomass of submerged vegetation varied much within the lake. At all three investigation occasions the macroalgae *Chara* was the overall dominating group and it was the only species sampled in both June and July. In September some of the samples contained also the cryptogam *Najas marina* (Swedish *havsnajas*).

Large areas without vegetation were noted at all three occasions. At the same time, very dense stands of *Chara* were also present within the lake. Accordingly, the distribution of the biomass values is very skewed (most values are low and a few are very high) (Figure 5-1), and therefore median values were used in further calculations.

The biomass varied over the growing season (Figure 5-2). Highest biomass value was recorded in July (median 209 g dw m^{-2}, 81 and 51 g dw m^{-2} in June and September, respectively), whereas the highest maximum value was recorded in September (1,774 g dw m^{-2}, 1,068 and 1,239 g dw m^{-2} in June and July, respectively). The median carbon biomass for the whole summer (n=60) was 21 g C m^{-2}. Using the median biomass of the 60 samples in the calculation of lake total biomass gives a total biomass of submerged vegetation in Lake Bolundsfjärden of 15,700 kg dw or 4,200 kg C.

No correlations between water depth and biomass were found ($r = -0.04$, $p > 0.05$).

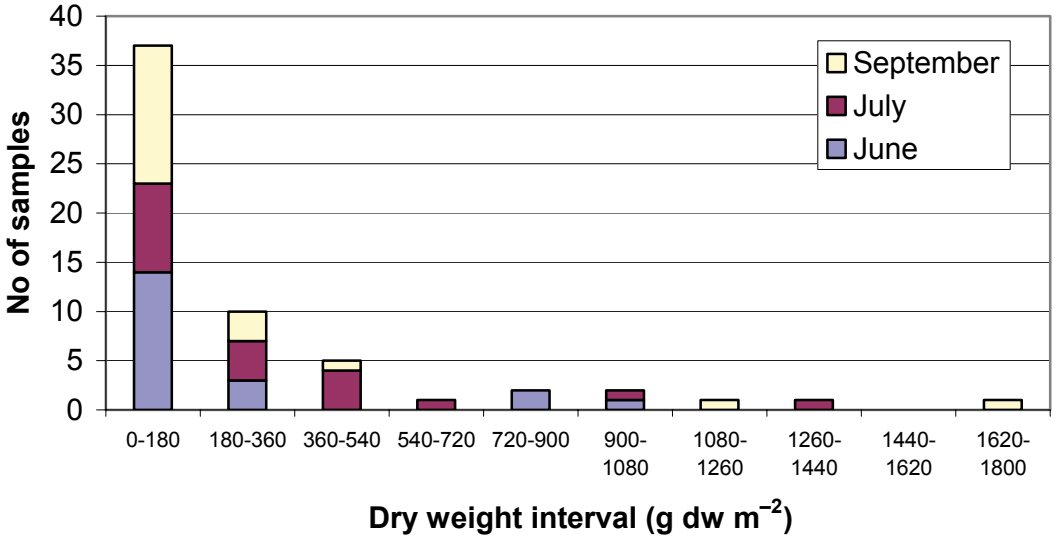

Figure 5-1. *Number of samples in different biomass intervals for submerged vegetation in Lake Bolundsfjärden in June, July and September 2006 (g dw m^{-2}).*

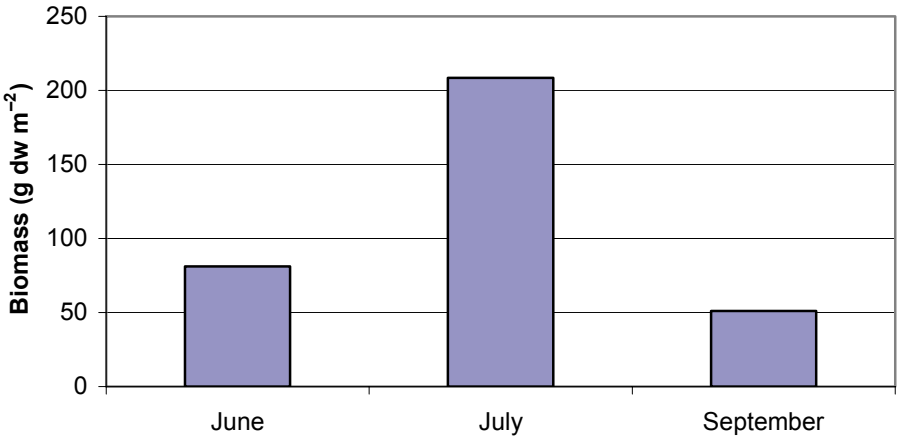

Figure 5-2. *Biomass of submerged vegetation in Lake Bolundsfjärden (g dw m^{-2}). Median values for June, July and September 2006.*

5.2 Production and respiration

As mentioned in Section 4.5, two different types of bottles were used in July and September as the ones used in June underestimate the oxygen concentration. The measurements in the different bottles are presented separately in Figure 5-3. When comparing the production between dates, results from the bottles of type I are used. The highest production (and respiration) per unit dry weight occurred during early summer (Figure 5-3). The production per unit area, on the other hand, was highest in July as the biomass per m^{-2} was much higher at this time. The production per unit area was 108, 222, and 33 mg O_2 m^{-2} h^{-1} in June, July and September, respectively. If results from the bottles of type II are used, the production per unit area in July and September was 379 and 34 mg O_2 m^{-2} h^{-1}, respectively. Thus, the production by bottle nr I was underestimated by 70% in July whereas the underestimation in September was small, only 5%.

Two of the production replicates in September were measured on *Najas marina*. There was an indication of higher production by *Najas marina* (mean 1.0 mg O_2 g dw^{-1} h^{-1}, n=2) compared to the production by *Chara* (mean 0.6 mg O_2 g dw^{-1} h^{-1}, n= 8), but the low number of replicates prevents us to do any statistical analyses. The number of *Najas* replicates corresponds to the occurrence in biomass samples.

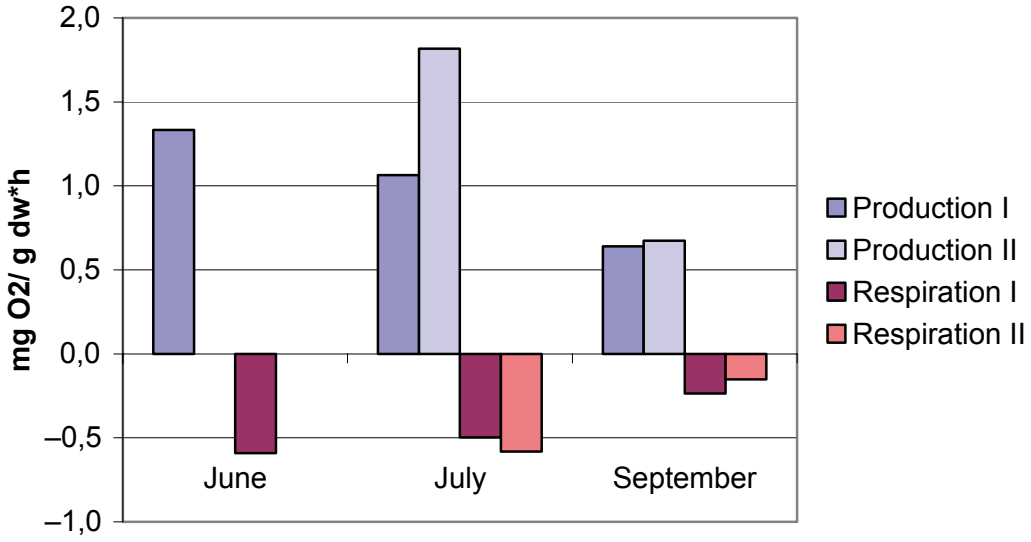

Figure 5-3. *Production and respiration at the three measurement occasions. Measurements in different types of bottles are shown separately (I and II respectively).*

The global radiation at the three sampling dates monitored at the site Stormasten in Forsmark (PFM010700) is presented in Figure 5-4. The solar insolation was highest in June, but the production per unit energy was highest in September; 0.0028 mg O_2 g dw^{-1} kJ^{-1} m^2 compared to 0.0005 and 0.0007 in June and July, respectively. Using the production values gained in the bottles of type II (used only in July and September), the production values per unit energy were 0.0011 mg O_2 g dw^{-1} kJ^{-1} m^2 in July and 0.0029 mg O_2 g dw^{-1} kJ^{-1} m^2 in September.

The annual production in Lake Bolundsfjärden during 2006, calculated with results from the type I bottles, was 252 g O_2 m^{-2} y^{-1}. The annual production calculated with results from the type II bottles for July and September, was considerably higher, 344 g O_2 m^{-2} y^{-1} (Table 5-1). Corresponding carbon production was 79 g C m^{-2} y^{-1} with type I bottles and 108 g C m^{-2} y^{-1} with type II bottles.

5.3 Distribution

There were large areas along the border of the lake that lacked submerged vegetation. The observations made in June are presented in Appendix 4. In addition, also areas within the lake were empty of vegetation. The empty areas were accounted for in the biomass estimation, as areas lacking vegetation were also included in the random selection of sampling sites.

Table 5-1. Cumulative global radiation (W m^{-2}) during the estimated vegetative period in 2006 and calculated annual production for this period using either of the two production values measured in the two different types of glass bottles.

Year	Global radiation Ice break – 30 September MW m^{-2}	Production Bottles type I g O_2 m^{-2} y^{-1}	Production Bottles type II g O_2 m^{-2} y^{-1}
2006	2,685	252	344

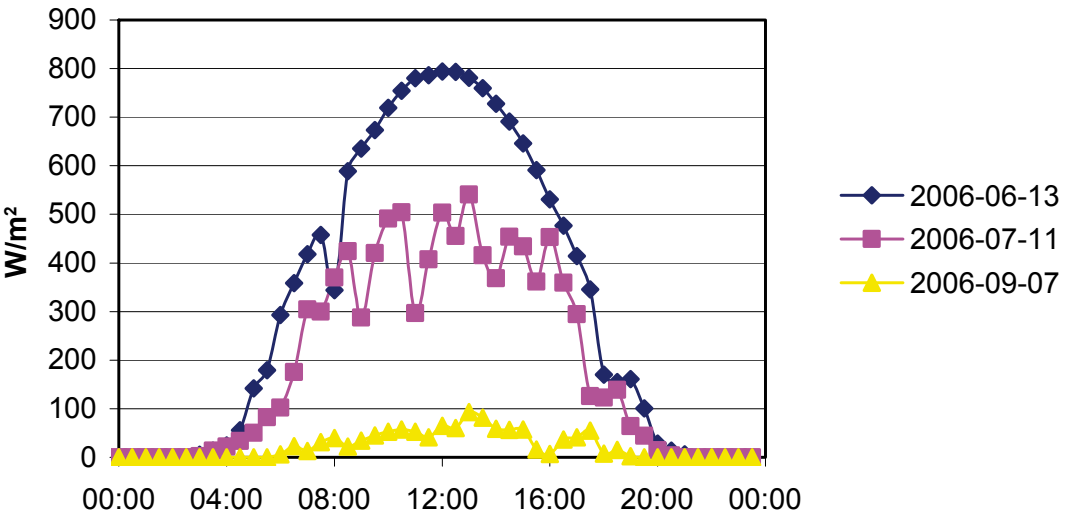

Figure 5-4. *Global radiation at Stormasten (PFM010700) during the three days when primary production of submerged vegetation was measured in Lake Bolundsfjärden, (from http://www.airviro.smhi.se/forsmark/).*

6 Summary and discussions

6.1 Comparison with other studies

Biomass of submerged vegetation has been registered within the Forsmark area in two earlier studies. In September 2004, bottom vegetation was investigated in Lake Bolundsfjärden and Lake Fiskarfjärden /Huononen 2005/. The shallow bottoms of the bay Kallrigafjärden were investigated in August the same year /Borgiel 2005/. Data from these two studies are presented in Table 6-1. In the first study, the sample locations were divided into littoral I and littoral III. We do not agree with the author's view of habitat borders and treat all samples as samples from littoral III. In Table 6-1, the median values of all ten samples in each lake are presented, together with median values for Kallrigafjärden.

The biomass from September in our study was of the same order of magnitude as in the previous studies, although with somewhat lower values than in the study from Lake Bolundsfjärden in 2004. The much higher value in July and also higher value in June indicate that an annual estimation based on late summer values underestimates the biomass. The biomass was lower than in Kallrigafjärden but the comparison between this location and Lake Bolundsfjärden is difficult and less relevant since Kallrigafjärden is a brackish bay whereas Lake Bolundsfjärden is a freshwater location.

Data on *Chara* biomass from other sites are compiled in /Kufel and Kufel 2002/. The values vary between 42 and 500 g dw m^{-2}. The median value from Lake Bolundsfjärden (83 g dw m^{-2}) is in the lower range of these estimates. On the other hand, the maximum values in our study, 1,774 g dw m^{-2}, is very high. In the review by /Kufel and Kufel 2002/, two Swedish lakes are included (Lake Tåkern and Lake Krankesjön). Both these lakes have high biomass values (465 and 478 g dw m^{-2} respectively). One explanation to the higher biomass in these two lakes could be that they are situated further south in Sweden and thus receive higher solar insolation. They are also more nutrient rich and have higher phosphorus concentrations than Lake Bolundsfjärden /Blindow 1992/. Fewer studies deal with biomass of *Najas marina* compared to *Chara*. In a study from Australia *Najas marina* had a biomass between 99 and 185 g dw m^{-2} /Royle and King 1991/. This is more than twice the biomass estimates in this study (*Najas marina* biomass varied between 12 and 53 g dw m^{-2}). In Australia, the distribution of *Najas marina* was shown to vary much between years and it is possible that the distribution varies also in Lake Bolundsfjärden.

Table 6-1. Biomass of submerged vegetation in studies from the Forsmark area.

	Median value (g dw m^{-2})	Minimum value (g dw m^{-2})	Maximum value (g dw m^{-2})	Number of samples
Bolundsfjärden (this study)				
June – September 2006	83	0	1,774	60
June 2006	81	0	1,069	20
July 2006	209	0	1,239	20
September 2006	51	0	1,774	20
Bolundsfjärden /Huononen 2005/				
September 2004	99	0	2,005	10
Fiskarfjärden /Huononen 2005/				
September 2004	43	0	934	10
Kallrigafjärden /Borgiel 2005/				
August 2004	156	149	189	3

Some data concerning *Chara* primary production and respiration are presented by /Kufel and Kufel 2002/ (Table 6-2). /Pereyra-Ramos 1981/ studied the production in Lake Majcz Wielki in northern Poland. He reported a maximum net production in July of 26 mg O_2 g dw^{-1} 24 h^{-1}. This is similar to our net production in July (19 mg O_2 g dw^{-1} 24 h^{-1}). In September on the other hand, his net production was close to zero, whereas we found a net production of almost 6 mg O_2 g dw^{-1} 24 h^{-1}. Compared to /Hough and Putt 1988/, on the other hand, our production is very low. They reported a production of 1–13 mg C g^{-1} h^{-1}, whereas the production in our study varied between 0.2 and 0.6 mg C g^{-1} h^{-1}. To conclude, our production is within reported values. Some are though much higher, but there are also lower values.

The primary production and respiration of *Chara* have also been investigated in a *Chara* meadow in the shallow bay Kallrigafjärden within the Forsmark area /Borgiel 2006/. In that study, plexiglass containers were placed on the bottom and the oxygen concentration inside the containers was recorded during 24 hours. In this way the net primary production of the benthic community is measured during daytime and respiration is measured during night. In July the production seems to strongly increase at about 9 pm and continues until about 6 am. Then the oxygen curve turns again and the respiration dominates. Our measurements were performed during the time period 10 pm–2 am which is well within the time span where production dominates in the former study. If the incubation had proceeded longer there may have been bottle effects, i.e. that the size of the bottle volume had an impact on the results. If the incubations had continued after 6 am it had been difficult to interpret what the results had represented.

6.2 Distribution

The values of production and respiration per unit weight can, in combination with biomass values per unit area, be used to estimate primary production and respiration for the whole lake. If large bottom areas lack submerged vegetation, the estimation of primary production within the lake will be overestimated if this is not compensated for. During the first investigation occasion we rowed along the shoreline of the entire lake and registered areas empty of vegetation. The purpose was to make up a map in GIS. When biomass sampling was performed, it was discovered that small or larger areas within the lake also lacked submerged vegetation, and to make up a complete map of empty areas we had to do observations in transects all over the lake. This was considered too time consuming, and to provide a more realistic biomass estimation also areas lacking submerged vegetation were included in the biomass sampling.

Table 6-2. Primary production values from this study and studies compiled in /Kufel and Kufel 2002/.

Study	Parameter	Value
This study	**Net production (O_2)**	
	June	13.2 mg O_2 g dw^{-1} $24h^{-1}$
	July (bottle II)	19.3 mg O_2 g dw^{-1} $24h^{-1}$
	September (bottle II)	5.7 mg O_2 g dw^{-1} $24h^{-1}$
This study	**Net production (C)**	
	June	0.4 mg C g^{-1} h^{-1}
	July (bottle II)	0.6 mg C g^{-1} h^{-1}
	September (bottle II)	0.2 mg C g^{-1} h^{-1}
/Pereya-Ramos 1981/	**Net production (O_2)**	
	July	26.3 mg O_2 g dw^{-1} $24h^{-1}$
	September	0.6 mg O_2 g dw^{-1} $24h^{-1}$
/Hough and Putt 1988/	**Maximum production (C)** (early summer)	8–13 mg C g^{-1} h^{-1}
/Hough and Putt 1988/	**Minimum production (C)** (late summer)	1–3 mg C g^{-1} h^{-1}

6.3 Robustness and uncertainties

This study contains a larger number of replicates than earlier studies of biomass and production of submerged vegetation in lakes in the Forsmark area and is thus a more robust estimate of these parameters. However, there are some uncertainties in the study which are discussed below.

Large variation

The biomass samples showed large variation, and furthermore, the distribution of the samples was strongly skewed. By using the median values a more correct biomass estimate for the entire lake is accomplished compared to using mean biomass values. The best way of achieving a good estimate of the biomass would be to map the entire lake bottom with respect to the coverage of *Chara* (see Section 6.2). However, this is a very time consuming effort and we consider the median values of the biomass in Lake Bolundsfjärden good enough for the purpose of ecosystem modelling.

Different sets of glass bottles

The glass bottles used at the first sampling occasion (type I bottles) may lead to an underestimation of the production. Since there were small air bubbles in the bottles, oxygen produced during photosynthesis may have been released to the air bubbles and not detected in the readings of dissolved organic oxygen in the water. This was also noted in July and September when production was compared between two types of glass bottles with and without air bubbles. The production when using type I bottles was underestimated by 70% in July and 5% in September. There was also a potential limitation with the second set of glass bottles (type II bottles) as the oxygen probe did not fit in the glass bottles. The pouring of water into a vial for oxygen measurements may also have lead to an underestimation. However, this was done very carefully and should not have posed a large underestimation of the oxygen concentration.

When calculating the yearly production with data from the type II bottles for July and September, the production was almost 100 g dw m^{-2} y^{-1} higher than if calculated with only type I bottles. For the June sampling, only data from type I bottles were available, and thus also the estimation of annual production with data from type II bottles may be an underestimate, as type I bottles were used for the period from ice break to June 27. Assuming that the underestimation in June is somewhere between 5 and 70% (the underestimation measured at sampling in July and September) leads to an underestimation of annual production between 3 and 34 g O_2 m^{-2} in year 2006. This is a relatively small underestimate (c 1–10%) considering that the annual production in 2006 (measured with type II bottles in July and September) was 344 g O_2 m^{-2} y^{-1}. Thus, we believe that the annual production achieved in this study is a good estimate of the production in the Forsmark lakes and can be used for further modelling of the ecosystem.

Conversion factors

The conversion of measured data to other units is strongly dependent on which conversion factors that are used. In our study, we have used a conversion factor of 0.268 g C g dw^{-1} /Hannu and Karlsson 2006/. This is high compared to the conversion factor of 0.135 reported by /Kautsky 1995/. However, the conversion factor used in this study is measured on *Chara* in Lake Bolundsfjärden, and should thus be a reliable estimate. For the conversion between oxygen and carbon in production measurements we have used the factor 0.3125 g C g O_2^{-1} /Gutenstam 1979/. However, other conversion factors are also found in the literature /Kautsky 1995; 0.334, Wetzel and Likens 1991; 0.375/. However, the difference between these conversion factors is small and thus has only a minor impact on the end result.

Extrapolation of production to annual production

Production of phytoplankton can be assumed to be direct proportional to light /Wetzel and Likens 1991/. This is not true for the phytoplankton at the water surface but for the whole water column. We have assumed the same direct proportionality between light and submerged vegetation. However, the submerged vegetation is fixed at a certain depth in the water column and may thus be more dependent on light limitation or light saturation, which would affect this proportionality. Moreover, we have extrapolated the production from three sampling dates for the entire period from ice break in early April to late September. To extrapolate production from light for a few dates gives relatively accurate production values, whereas extrapolation for longer periods is more uncertain /Wetzel and Likens 1991/. Thus it is clear that our estimate of yearly production is associated with uncertainty. However, it is likely a good estimate of the order of magnitude of the production of submerged vegetation.

6.4 Conclusion

We have measured biomass and primary production of submerged vegetation in Lake Bolundsfjärden. Investigations were performed three times during the summer 2006. Stonewarts (*Chara*) dominated the biomass totally at all three occasions. In September, *Najas marina* was also present in some samples.

The biomass varied over time and was highest in July (median 209 g dw m^{-2}, compared to 81 and 51 g dw m^{-2} in June and September). These values are in the same order of magnitude as values from the same lake in 2004, and also from the nearby lake Fiskarfjärden (2004). The median carbon weight for the summer (n=60) was 21 g C m^{-2}. Calculation of the biomass of submerged vegetation for the whole lake from these figures results in a total biomass of 15,700 kg dw (4,200 kg C).

The primary production did also vary over time. The highest production per unit dry weight was found in June (1.3 mg O_2 g dw^{-1} h^{-1}) and the lowest in September (0.7 mg O_2 g dw^{-1} h^{-1}). The same was true for the respiration (0.6 mg O_2 g dw^{-1} h^{-1} in June and 0.2 mg O_2 g dw^{-1} h^{-1} in September). Looking at production per unit solar energy, the situation is totally different; the highest production value was found in September (0.0028 mg O_2 g dw^{-1} kJ^{-1} m^2), whereas the values for June and July were lower (0.0005/0.0007 mg O_2 g dw^{-1} kJ^{-1} m^2). The production per unit area was highest in July (222 mg O_2 m^{-2} h^{-1}, compared to 108 and 33 mg O_2 m^{-2} h^{-1} in June and September, respectively), which is expected since the biomass was very high at that time. Compared to other studies, our production values are within their range. Some values are much higher than ours but there are also lower values. When calculating annual production the figures vary according to the data set used; for measured production values one can choose values measured in glass bottles of type I or type II. Using the values we find most confidence in (production values for bottle II when available and type I otherwise) results in an annual production of about 344 g O_2 m^{-2} y^{-1} or 108 g C m^{-2} y^{-1}.

The results from the investigations are associated with a number of uncertainties. However, we suggest that the large number of replicates, and the accordance with other studies, implies that the results are of good quality and may be used for modelling of the ecosystems in Lake Bolundsfjärden, as well as other similar lakes in the same area.

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Appendix 1

Biomass values

Date: 2006-06-12. Area: 0.04 m^2.

Sample id	Depth (cm)	X-coordinate	Y-coordinate	Wet weight (g ww)	Dry weight (g dw)	Density (g dw m^{-2})	Density (g C m^{-2})
1	90	6698675	1631827	30.9	1.7360	43	12
2	90	6698839	1632027	24.9	1.6114	40	11
3	100	6698844	1632027	142.0	9.0401	226	60
4	100	6698844	1632027	117.1	7.3685	184	49
5	100	6698787	1632013	549.4	33.8885	847	227
6	100	6698787	1632013	71.0	4.6999	117	31
7	60	6698932	1631937	0.0	0.0	0	0
8	60	6698932	1631937	0.0	0.0	0	0
9	140	6698977	1632024	566.2	42.7339	1,068	286
10	140	6698977	1632024	503.2	29.4291	736	197
11	170	6699022	1632072	0.0	0.0	0	0
12	170	6699022	1632072	0.0	0.	0	0
13	90	6698990	1631975	33.0	1.9213	48	13
14	90	6698990	1631975	32.5	2.1355	53	14
15	80	6698862	1631935	10.7	0.5106	13	3
16	80	6698862	1631935	112.0	7.0054	175	47
17	90	6698810	1631904	28.8	1.7923	45	12
18	90	6698810	1631904	113.3	6.4362	161	43
19	80	6698780	1631868	87.5	7.7996	195	52
20	80	6698780	1631868	51.8	4.3542	109	29
			Mean:	123.7	8.1231	203	54
			Standard deviation:	184.4	12.2833	307	82
			Median:	42.4	3.2449	81	22

Date: 2006-07-10. Area: 0.04 m^2.

Sample id	Depth (cm)	X-coordinate	Y-coordinate	Wet weight (g ww)	Dry weight (g dw)	Density (g dw m^{-2})	Density (g C m^{-2})
1	60	6699097	1632453	96.6	13.5757	339	91
2	60	6699097	1632453	320.6	41.6851	1,042	279
3	60	6699130	1632320	187.9	23.7144	593	159
4	60	6699130	1632320	58.1	6.5795	164	44
5	110	6699178	1632219	4.5	0.1344	3	1
6	110	6699178	1632219	3.4	0.0873	2	1
7	90	6699237	1632122	95.9	8.4633	212	57
8	90	6699237	1632122	136.0	16.0533	401	107
9	125	6699226	1632092	0.0	0.0	0	0
10	125	6699226	1632092	0.0	0.0	0	0
11	115	6699118	1632048	25.3	2.1216	53	14
12	115	6699118	1632048	1.5	0.0806	2	1
13	80	6698971	1631993	236.7	19.4728	487	130
14	80	6698971	1631993	99.3	8.2201	206	55
15	100	6698824	1631978	386.5	49.5406	1,239	331
16	100	6698824	1631978	220.6	21.033	526	141
17	80	6698802	1631930	13.1	1.1891	30	8
18	80	6698802	1631930	225.6	21.406	535	143
19	90	6698771	1631894	76.8	9.7555	244	65
20	90	6698771	1631894	4.3	0.5525	14	4
			Mean:	109.6	12.1832	305	81
			Standard deviation:	116.9	14.1261	353	94
			Median:	86.4	8.3417	209	56

Date: 2006-09-06. Area: 0.04 m^2.

Sample id	Depth (cm)	X-coordinate	Y-coordinate	Wet weight (g ww)	Dry weight (g dw)	Density (g dw m^{-2})	Density (g C m^{-2})
1		6698789	1631874	86.4	10.1997	255	68
2		6698789	1631874	146.7	19.0328	476	127
3		6698877	1631903	27.0	1.3893	35	9
4		6698877	1631903	81.8	7.9345	198	53
5		6698927	1631995	3.9	0.2805	7	2
6		6698927	1631995	3.5	0.1923	5	1
7		6698945	1631991	485.5	70.9729	1,774	475
8		6698945	1631991	355.6	44.2037	1,105	296
9		6698952	1632025	40.6	2.1353	53	14
10		6698952	1632025	49.1	1.9417	49	13
11		6698962	1632068	0.0	0.0	0	0
12		6698962	1632068	0.0	0.0	0	0
13		6698955	1632100	62.6	7.365	184	49
14		6698955	1632100	26.9	3.5649	89	24
15		6698932	1632143	57.4	5.1112	128	34
16		6698932	1632143	32.3	3.0833	77	21
17		6698822	1632208	23.8	1.2296	31	8
18		6698822	1632208	9.5	0.4717	12	3
19		6698800	1632400	15.2	0.8538	21	6
20		6698800	1632400	17.3	0.9547	24	6
			Mean:	76.3	10.0509	226	60
			Standard deviation:	124.9	18.5001	444	119
			Median:	29.7	2.6093	51	14

Appendix 2

Data from production and respiration measurements

Date: 2006-06-12. Coordinates: 6698897, 1632000. Measurement depth: 0.9 m.

Production measurement

Bottle no	Start: 10:15 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Stop: 13:45 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Wet weight (g ww)	Dry weight (g dw)	Incub time (h)	Bottle vol (l)
L1	9.1	109.0	24.5	11.6	140.7	25.4	0.7	0.0464	3.5	0.10
L2	9.3	109.0	23.9	11.9	145.1	25.5	0.5	0.0320	3.5	0.10
L3	9.2	108.6	24.0	11.7	142.3	25.4	0.8	0.0436	3.5	0.10
L4	9.2	108.5	23.9	11.8	143.0	25.1	0.9	0.0638	3.5	0.10
L5	9.3	109.8	24.0	9.3	112.6	24.9	0.5	0.0434	3.5	0.10

Respiration measurement

Bottle no	Start: 10:15 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Stop: 13:45 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Wet weight (g ww)	Dry weight (g dw)	Incub time (h)	Bottle vol (l)
M1	8.5	101.8	24.6	7.8	93.8	24.5	0.4	0.0272	3.5	0.10
M2	9.4	111.2	24.1	8.7	103.8	24.3	0.5	0.0463	3.5	0.10
M3	9.0	107.7	24.6	8.5	100.7	24.3	0.3	0.0326	3.5	0.10
M4	9.1	109.4	24.9	7.6	90.8	24.6	0.6	0.0439	3.5	0.10
M5	9.2	110.8	24.8	8.4	100.1	24.4	0.5	0.0612	3.5	0.10

Date: 2006-07-11. Coordinates: 6698936, 1632046. Measurement depth: 0.9 m.

Production measurement

Bottle no	Start: 10:15 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Stop: 14:10 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Wet weight (g ww)	Dry weight (g dw)	Incub time (h)	Bottle vol (l)
L1	8.1	92.1	22.2	11.6	137.8	24.1	1.2	0.1253	3.9	0.10
L2	8.2	93.1	22.0	12.6	147.5	23.5	0.8	0.0766	3.9	0.10
L3	8.4	95.4	21.6	10.7	125.4	23.3	0.7	0.0834	3.9	0.10
L4	8.5	95.7	21.3	12.2	142.4	23.3	0.6	0.0686	3.9	0.10
L5	7.7	88.0	22.0	10.4	120.2	22.6	0.6	0.0653	3.9	0.10
L6	8.2[1]	93.9[1]	22.0[1]	11.6	134.8	22.8	0.7	0.0796	3.9	0.12
L7	8.2[1]	93.9[1]	22.0[1]	13.9	162.7	23.2	1.1	0.1080	3.9	0.12
L8	8.2[1]	93.9[1]	22.0[1]	12.8	149.4	23.3	0.9	0.0955	3.9	0.12
L9	8.2[1]	93.9[1]	22.0[1]	13.3	154.3	23.0	0.6	0.0579	3.9	0.13
L10	8.2[1]	93.9[1]	22.0[1]	12.5	145.4	23.0	0.7	0.0712	3.9	0.13

Respiration measurement

Bottle no	Start: 10:15 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Stop: 14:10 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Wet weight (g ww)	Dry weight (g dw)	Incub time (h)	Bottle vol (l)
M1	8.2	94.5	22.4	7.5	87.2	22.7	0.4	0.0382	3.9	0.10
M2	8.5	97.2	22.5	6.8	78.5	22.5	0.8	0.0800	3.9	0.10
M3	8.2	94.0	22.1	6.9	79.8	22.5	0.7	0.0762	3.9	0.10
M4	8.2	93.1	22.1	7.4	85.4	22.7	0.7	0.0507	3.9	0.10
M5	8.4	96.1	22.0	7.4	84.8	22.5	0.4	0.0397	3.9	0.10
M6	8.2[1]	93.9[1]	22.0[1]	7.2	83.2	22.8	0.5	0.0509	3.9	0.12
M7	8.2[1]	93.9[1]	22.0[1]	7.2	83.3	22.4	0.5	0.0635	3.9	0.12
M8	8.2[1]	93.9[1]	22.0[1]	7.0	80.4	22.6	0.4	0.0584	3.9	0.12

[1] Oxygen and temperature could not be measured directly into each bottle, average start values for L1–L5 and M1–M5 have been used.

Date: 2006-09-07. Coordinates: 6698782; 1631857. Measurement depth: 0.9 m.

Production measurement

Bottle no	Start: 10:20 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Stop: 14:20 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Wet weight (g ww)	Dry weight (g dw)	Incub time (h)	Bottle vol (l)
L1	9.3	93.6	15.2	12.6	127.9	15.3	1.1	0.1390	4.0	0.10
L2	9.6	96.0	14.9	11.9	120.2	15.3	1.3	0.1217	4.0	0.10
L3	8.5	86.1	15.6	11.8	119.4	15.3	1.2	0.0612	4.0	0.10
L4	8.1	82.1	15.3	11.2	113.5	15.3	1.4	0.1741	4.0	0.10
L5	8.0	80.8	15.4	10.0	100.3	15.1	1.2	0.1480	4.0	0.10
L6	8.8[2]	88.5[2]	15.2[2]	12.3	126.7	16.0	1.2	0.1046	4.0	0.12
L7	8.8[2]	88.5[2]	15.2[2]	10.3	104.8	15.5	1.0	0.0644	4.0	0.12
L8	8.8[2]	88.5[2]	15.2[2]	12.2	124.4	15.6	1.9	0.1944	4.0	0.12
L9	8.8[2]	88.5[2]	15.2[2]	11.5	117.7	15.6	0.9	0.1448	4.0	0.13
L10	8.8[2]	88.5[2]	15.2[2]	12.3	124.8	15.5	0.6	0.1911	4.0	0.13

Respiration measurement

Bottle no	Start: 10:20 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Stop: 14:20 Oxygen conc (mg l^{-1})	Oxygen conc (%)	Temp °C	Wet weight (g ww)	Dry weight (g dw)	Incub time (h)	Bottle vol (l)
M1	9.2	92.5	15.2	8.5	86.2	15.3	0.8	0.0942	4.0	0.10
M2	8.9	89.0	15.0	7.0	71.1	15.2	1.8	0.2647	4.0	0.10
M3	8.7	87.6	15.2	7.1	71.1	15.0	1.7	0.1169	4.0	0.10
M6	8.8[2]	88.5[2]	15.2[2]	8.4	84.9	15.1	1.1	0.1187	4.0	0.12
M7	8.8[2]	88.5[2]	15.2[2]	8.4	84.6	15.0	0.6	0.0845	4.0	0.12
M8	8.8[2]	88.5[2]	15.2[2]	7.0	71.3	15.3	1.8	0.2319	4.0	0.12

[2] Oxygen and temperature could not be measured directly into each bottle, average start values for L1–L5 and M1–M3 have been used.

Appendix 3

Calculated production and respiration values

Data calculated using measurement data from 2006-06-13 (see Appendix 2):

Bottle no	Net primary production (mgO_2 g dw^{-1} h^{-1})	Net primary production (mgO_2 m^{-2} h^{-1})	Bottle no	Net respiration (mgO_2 g dw^{-1} h^{-1})	Net respiration (mgO_2 m^{-2} h^{-1})
L1	1.5	124.9	M1	0.7	59.6
L2	2.3	188.3	M2	0.4	35.0
L3	1.6	132.9	M3	0.4	35.5
L4	1.2	94.5	M4	1.0	79.2
L5	0.0	0.0	M5	0.4	30.3
Mean	*1.3*	*108.1*	*Mean*	*0.6*	*47.9*

Data calculated using measurement data from 2006-07-11 (see Appendix 2):

Bottle no	Net primary production (mgO_2 g dw^{-1} h^{-1})	Net primary production (mgO_2 m^{-2} h^{-1})	Bottle no	Net respiration (mgO_2 g dw^{-1} h^{-1})	Net respiration (mgO_2 m^{-2} h^{-1})
L1	0.7	148.7	M1	0.5	97.6
L2	1.5	305.8	M2	0.5	113.1
L3	0.7	146.8	M3	0.4	90.8
L4	1.4	287.2	M4	0.4	84.0
L5	1.1	220.2	M5	0.6	134.1
Mean L1–L5	*1.1*	*221.7*	*Mean M1–M5*	*0.5*	*103.9*
L6	1.2	258.5	M6	0.6	128.4
L7	1.6	329.3	M7	0.5	102.9
L8	1.4	297.5	M8	0.6	132.3
L9	2.9	595.6			
L10	2.0	414.1			
Mean L6–L10	*1.8*	*379.0*	*Mean M6–M8*	*0.6*	*121.2*
Mean L1–L10	*1.4*	*300.4*	*Mean M1–M8*	*0.5*	*110.4*

Data calculated using measurement data from 2006-09-07 (see Appendix 2):

Bottle no	Net primary production (mgO_2 g dw^{-1} h^{-1})	Net primary production (mgO_2 m^{-2} h^{-1})	Bottle no	Net respiration (mgO_2 g dw^{-1} h^{-1})	Net respiration (mgO_2 m^{-2} h^{-1})
L1	0.6	30.2	M1	0.2	9.5
L2	0.5	24.1	M2	0.2	9.1
L3	1.3	68.7	M3	0.3	17.4
L4	0.4	22.7			
L5	0.3	17.2			
Mean L1–L5	*0.6*	*32.6*	*Mean M1–M3*	*0.2*	*12.0*
L6	1.0	49.2	M6	0.1	4.9
L7	0.7	35.3	M7	0.1	6.9
L8	0.5	26.2	M8	0.2	11.5
L9	0.6	30.5			
L10	0.6	30.4			
Mean L6–L10	*0.7*	*34.3*	*Mean M6–M8*	*0.2*	*7.8*
Mean L1–L10	*0.7*	*33.5*	*Mean M1–M8*	*0.2*	*9.9*

Appendix 4

Distribution of submerged vegetation along the borders of Lake Bolundsfjärden in June 2006

Observation point

0 75 150 300 m

N

From GSD-Fastighetskartan © Lantmäteriverket Gävle 2001. Consent M2001/5268

2006-10-16, 18:00