Collecting in situ remote sensing reflectances of submersed macrophytes to build up a spectral library for lake monitoring

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Abstract
To map the aquatic vegetation of Bavarian (Germany) freshwater lakes in a large-scaled and quick way, remote sensing is a helpful tool. For interpretation of the data, a spectral library of different macrophyte and sediment reflectances is under development. Therefore, multi-temporal in situ remote sensing reflectances were sampled from May to October 2011 with hyperspectral RAMSES spectroradiometers. Occurring spectral variations during the growing season could be linked to biometric and phenological data of the particulate species. Principal component analyses showed that, by applying the presented method, differentiation of the macrophytes from sediment and among each other is possible and can be improved by multi-temporal data.

Keywords: submersed macrophytes, phenology, spectral library, RAMSES, PCA.

Introduction
Submersed macrophytes play an important role in lake ecosystems as habitats for producers of oxygen or different organisms [Pieterse and Murphy, 1990; Schultz and Dibble, 2012] as well as in the accumulation and recycling of nutrients [Marion and Paillisson, 2003]. In addition, their use as indicator plants for the trophic state of a lake is well explored [Melzer, 1987; Malthus et al., 1990; Moss, 1990; Onaindia et al., 1996; Melzer, 1999]. Hence, the massive expansion of invasive macrophytes like *Elodea nuttallii* and *Najas marina* influences lake ecosystems in terms of habitat structures, water characteristics, biodiversity and nutrient cycles [Carignan and Kalff, 1980; Thomaz and da Cunha, 2010; Schultz and Dibble, 2012]. While *Elodea nuttallii* is a neophyte, *Najas marina* is indigenous and supposed to be promoted by increasing water temperatures due to climate change. To monitor these processes by common field methods is often difficult, as populations might be difficult to access [Vis et al., 2003; Hestir et al., 2008] and the effort in money, time and logistics is very high [Hestir et al., 2008]. Additionally, direct contact by scientific divers contributes to plant fragmentation and therefore its dispersal [Bossard et al., 2001].
Regular monitoring based on remote sensing methods can help to avoid these issues. Various authors have shown the potential to identify aquatic vegetation with different remote sensing systems [Malthus and George, 1997; Heege et al., 2003; Williams et al., 2003; Pinnel, 2007; Ma et al., 2008; Yuan and Zhang, 2008; Heblinski et al., 2011]. Nevertheless, considerable challenges have to be overcome for a successful monitoring. Within a pre-processing chain the plant signal must be separated from external influences. Above the water body the main attenuation sources are cloud coverage, illumination and viewing angles of the system and roughness of water surface [Mertes et al., 1993; Bostater et al., 2004; Morel and Belanger, 2006]. Below the water surface, effects of the overall water column [Mumby et al., 1998; Silva et al., 2008] have to be considered, as water itself or suspended and dissolved materials affect radiative transfer [Mobley, 1994]. In order to control the atmospheric and water column corrections of remote sensing data, it is very helpful to know the reflectance spectra of the lake bottom. Hence, it is necessary to collect the reflectance spectra of plants or sediments just above the vegetation canopies and sediments [Pinnel, 2007; Heblinski et al., 2011]. Finally, species composition and canopy structure of the vegetation at sampling date [Hestir et al., 2008] are required for a monitoring by remote sensing methods.

To comply with these demands, the present study a) introduces advancements of a method [Pinnel, 2007] for sampling, processing and analysing multi-seasonal in situ reflectance spectra of the submersed macrophytes *Elodea nuttallii*, *Najas marina*, *Chara* spp. and *Potamogeton perfoliatus* and b) evaluates the effects of particular phenological characteristics of the single species on their spectral response. A third aim was to evaluate, if phenological “spectral fingerprints” of the plants could enforce their monitoring. To visualize differences of the spectral shapes at different phenological stages between as well as within the species, principal component analyses (PCA) were performed.

**Methods**

**Study site**

Test site selection was guided by the occurrence of populations of the invasive species *Elodea nuttallii* and *Najas marina* at Lake Tegernsee (47.7°N, 11.7°E) and Lake Starnberg (48.0°N, 11.3°E), both located south of Munich, in Upper-Bavaria, Germany. A third site at Lake Starnberg allowed simultaneous studies on populations of *Chara aspera* and *Potamogeton perfoliatus*. Pure populations of *Elodea nuttallii* and *Najas marina* were developed at depths between 2 m and 4 m. Pure populations of *Chara aspera* and *Potamogeton perfoliatus* were only present at a depth of about 2 m. As the *Chara aspera* site is not composed of a pure population, but consists of 10% of *Chara delicatula* and *Chara intermedia*, this site was correctly named *Chara spp*. test site.

The test site Lakes Osterseen (47.8°N, 11.3°E) was chosen to validate the water column correction, which was part of the spectral data processing. Therefore, measurements at deep water areas were conducted in summer 2012.

**Biometric measurements**

For *Elodea nuttallii*, *Najas marina*, *Chara* spp. and *Potamogeton perfoliatus* biometric parameters like density, canopy height, biomass and pigment contents were measured during growing season always once a day at representative spots. For the determination
of biomass and pigment compositions, 0.25 m² and three single plant tips were harvested by scientific divers, respectively. The samples were transported to the laboratory in dark cooling boxes with lake water. The plant material of the harvested 0.25 m² was weighted to estimate biomass and the plant tips were immediately frozen until the following treatment. The pigments were extracted in 2 ml of 100% acetone by milling 12 mg of each plant tip with mortar and pestle. After centrifugation (10 min, 500 g, 4°C) with a SIGMA 1K15 centrifuge, 1ml of the supernatant was filtered through a 0.45µm Nylon filter into a brown glass vial. All operations were carried out under dark conditions.

The filtrate was analysed in a HPLC instrument from JASKO with a C-18 column (KNAUER GmbH) after the method of Kraay et al. [1992]. Due to the availability of standards, the amounts of Chlorophyll a and b and the Carotenoids Neoxanthin, Violaxanthin, Lutein and β-Carotin could be determined.

A special case in the phenological context was Najas marina, where taller growing male plants collapsed after pollinating the shorter growing female plants. The female plants collapsed after seeds have matured. Both processes led to a decrease in height and biomass of the population.

**Reflectance measurements**

Remote sensing reflectance spectra \( (R_{rs}) \) were collected systematically from pure stands of four different macrophytes and their sediments. For this purpose a measurement set-up with RAMSES submersible spectroradiometers (TriOS GmbH) was placed at a distance of 3 meters from a boat or a terrestrial platform (Fig. 1). An optimal sun-object-sensor geometry was chosen all the time for avoiding shading effects and minimising neighbourhood effects. The boat was secured by two ropes to inhibit drifting during measurement. Depending on the test site, the ropes were fixed to wooden poles, which were driven into the sediment by scientific divers prior to the campaign and/or to trees on the shore. The terrestrial platform was stationary. An underwater stereo camera system was mounted to monitor the positions of the sensors and document the measured spots. Hemispherical downwelling irradiance \( (E_d) \) and upwelling radiance \( (L_u) \) with a field of view of 7° data were collected simultaneously in a range from 320 nm to 950 nm with a 3.3 nm step. These measurements were carried out just above the vegetation canopy (depth ‘b’) as well as just beneath the water surface (depth ‘0-‘). Depths were measured by a depth sensor, integrated in one of the RAMSES spectrometers. The distance between sensors and plant canopy or sediment was 20 cm and supervised by a live stream of the Canon cameras on the laptop. Information about canopy heights provided an additional depth control. As the standard deviations of the depth measurements were always ±3 cm, the boat set-up is assumed to have a similar stability than the terrestrial one. In the latter case a fluctuation of the sensors could be excluded. The stable set-up in case of the boat could be warranted by the wind-shaded position of the test sites, which caused a calm water surface.

The area covered by the \( L_u \)-sensor is 4.7 cm² at a distance of 20 cm to the object. Due to the high densities of the populations and the stable measurement set-up, this value was consistent during the growing season. At the stages of lower plant densities in June and July, underlying sediment became visible. As Elodea nuttallii, Najas marina and Chara spp. reached heights about 10 cm at this time, the sensor distance to the sediment increased to 30 cm (20 cm to plant plus 10 cm growing height). Therefore, the captured area enlarged
to 10.6 cm². This larger area and the low plant densities increased the influence of the sediment on the spectral response. For *Potamogeton perfoliatus*, where a tall but sparse population was present in July, the reflectance spectra were influenced by the surrounding water column (Fig. 7, blue plot).

Because of the quite similar spectral response of vegetation in general and submersed vegetation in this case, the key in distinguishing species and their mixture was seen in differing phenological developments. The aim was to figure out the phenological “spectral fingerprint” of each of the investigated species. Hence, the following experimental matrix was developed, to enable the linkage between phenological features and spectral response. At the test sites of *Elodea nuttallii, Najas marina, Chara spp.* and *Potamogeton perfoliatus*, spots of an area of 1 m² were defined at a depth of 2 m. As *Elodea nuttallii* and *Najas marina* were also present at 4m, an additional spot was defined in this depth, respectively. The spots were investigated from a pre-vegetation situation (pure sediment) in May 2011 and throughout the growing season, until vegetation collapsed in September or October 2011.
The locating of the spots during the year was warranted by markers on the shore and the ropes and by differential GPS. Every 3 weeks a field campaign was performed, were every test site was inspected. Measurements of one campaign - representing one phenological stage - were carried out within a time period of maximal one week. For example, the dates 10.08.2011, 11.08.2011 and 12.8.2011 were denoted as ‘August (begin)’. Further sampling intervals were ‘May’, ‘June’, ‘July’, ‘August (end)’, ‘September’ and ‘October’. Due to weather conditions and logistical reasons, only 2 sites were sampled in the months of June and July, respectively. In October the populations of *Chara* spp. and *Potamogeton perfoliatus* have already disappeared.

To account for changing sun positions across the course of a day the data collection started in the morning hours and lasted up to late afternoon. If measurement conditions were not ideal (due to strong waves, cloud coverage or sensor blackouts), it was recorded in the field book, so the dataset could be identified and excluded for further analysis. Therefore, on average six data sets were collected per day in the space of the defined spots. At three measurement days solely one or two data sets per day could be registered. In line with Pinnel [2007] one of these data sets consists of 20 replicates, which were measured within 3 minutes and at a fixed position. In addition to the data collected in depth ‘b’, 20 measurements in depth ‘0-’ were carried out afterwards in the same way and at the same position for water column corrections.

The validation of the water column correction process was carried out at Lakes Osterseen. Therefore, similar spectral measurements were carried out at deep water areas, together with sampling in situ water samples, which were analysed in the laboratory.

**In situ data of water constituents**

To derive concentrations of Chl-a and SPM at Lakes Osterseen, water samples were analysed in the laboratory, following the methods DIN 38412 L16 and DIN 38409 H2. To determine cDOM, a water sample was filtered through a 0.4µm cellulose acetate filter (Sartorius Stedim Biotech). Afterwards, the filtrate was analysed photometrical, following the method of Gege [2004a].

**Data processing**

The spectral data was processed with Python (version 2.7). From the 20 replicate measurements of $E_d$ and $L_u$ in depths ‘b’ and ‘0-’ per data set, 20 remote sensing reflectances ($R_{\text{rs}}(b)$ and $R_{\text{rs}}(0-)$) were calculated respectively and then smoothed by Savitzky-Golay-Filters of length 5 [Savitzky and Golay, 1964] to reduce sensor noise. Afterwards, the median for this set was calculated as it is more robust against outliers than the mean value. Due to strong noise outside the range of 400 nm and 700 nm (Fig. 3, right), spectra were cut at these wavelengths [Pinnel, 2007]. Furthermore, Armstrong [1993] mentioned that wavelengths above 700 nm have to be excluded, due to the high attenuation by water. The remaining water column of 20 cm between sensors and canopy was corrected according to a) absorption models for phytoplankton [Bricaud et al., 1995] and coloured dissolved organic matter (cDOM) [Giardino et al., 2012]; to b) backscattering models for phytoplankton [Brando and Dekker, 2003] and non-algal particles [Giardino et al., 2012] as well as absorption and backscattering coefficients of water; and to c) the radiative transfer model of Albert and Mobley [2003]. According to [Giardino et al., 2012] the absorption of
non-algal particles was left out. The required water constituent concentrations (Chlorophyll a (Chl-a), coloured dissolved organic matter (cDOM) and suspended particulate matter (SPM)) were derived by the inversion of the diffuse vertical attenuation coefficient for downwelling irradiance $K_d$ as implemented in the water colour simulator WASI [Gege, 2004b]). $K_d$ itself was calculated according to Maritorena [1996] using $E_d$-measurements in two different depths (‘b’ and ‘0-’). A verification of inversion results with in situ data was carried out at Lakes Osterseen in 2012.

To show the influence of a single constituent on the attenuation of downwelling irradiance in general, $K_d$ spectra were simulated with WASI for typical ranges of concentrations (Chl-a: 1-10 µg/l; cDOM: 0.2-0.7 m$^{-1}$; SPM: 0.1-5 mg/l) while keeping the other two components constant (Chl-a: 5 µg/l; cDOM: 0.4 m$^{-1}$; SPM: 3 mg/l).

**Principal component analysis (PCA)**

To visualize spectral differences between dense and sparse populations and sediments and differences within the single macrophytes groups, principal component analysis (PCA) was performed with the R-software (version 2.10, LinDA package). The evaluated wavelengths range covered the spectra between 400 nm and 700 nm.

**Results and Discussion**

**Biometric measurements**

The growths of all macrophytes started in the month of June and lead to complete coverage at the beginning of August. *Chara* spp. and *Potamogeton perfoliatus* decayed in September, whereas *Elodea nuttallii* and *Najas marina* decayed in October. The developments of biomasses and canopy heights corresponded to these processes and had their particular highest values in the month of August. In case of *Najas marina* the decay was overlain by the ongoing development of the female plants.

The different pigment contents of the single macrophytes could not be linked to our measured spectral reflectances. Schulze and Caldwell [1995] mention that “changes in chlorophyll content (…) are probably not a major factor in regulating light interception in natural situations” (page 26), as the absorbance is not linearly dependent due to the adaption of the absorption bands. However, the decreasing Chlorophyll a/Carotenoids ratio might be the reason of the flattened reflectance spectra of *Potamogeton perfoliatus/Elodea nuttallii* in September/October. In general, the comparison between spectral shapes and the pigmentations derived from plant tips may be insufficient.

**Water column correction**

The plots of the simulated $K_d$ spectra (Fig. 2) showed a decreasing influence from cDOM to Chl-a to SPM onto the light attenuation in the water column. Therefore, the inversion of $K_d$ has to be accurate in particular for cDOM. Validations of the fitted concentrations with in situ measurements did not exist for the test sites at Lake Starnberg and Lake Tegernsee. Nevertheless, high correlations for cDOM were found at Lakes Osterseen. In case of Chl-a, correlations were low. As the attenuation factor is only minimal influenced by SPM, WASI gave out the lowest possible value, which was 0.1 in this case.

Although further optimization is required (e.g. water sampling at particular date and position), uncertainties concerning the concentrations of water constituents are assumed to
have solely marginal influences, due to a thickness of the corrected water column of only 20 cm. To support this hypothesis, the left plot in Figure 3 shows the median prior to (red solid) and three version of it after the water column correction (green dotted, dashed and solid). The difference between the three versions is the content of Chl-a. Water column correction was performed with the fit result 6.7 µg/l and with the half (3.35 µg/l) and twice of it (13.4 µg/l). cDOM and SPM were 0.37 m⁻¹ and 0.1 mg/l in all three cases.

![Figure 2 - Influences of the water constituents cDOM, Chl-a and SPM onto the attenuation of downwelling irradiance. Spectra were simulated in WASI for typical concentration values.](image)

![Figure 3 - left: Uncorrected (red solid) and three corrected median spectra of *Najas marina*. Correction was performed with constant cDOM (0.37 m⁻¹) and SPM (0.1 mg/l) and varying Chl-a concentrations (3.35 µg/l green dotted, 6.7 µg/l green dashed, 13.4 mg/l green solid); right: Intensities of downwelling irradiance at different depths. Range from 700 nm to 950 nm at depths 1.3 m and 3 m is zoomed to show noise.](image)

**Reflectance measurements**

In Figures 4 to 7 sequences of the spectra (plots) over the growing season are given together with photographs of the measured spot at the respective phenological stage of the population (top view photographs). The green lines show the $R_{\text{rs}}$-spectra of the investigated species between 400 nm and 700 nm. All plant reflectance curves had typical vegetation features with higher reflectance values in the green and at the red edge and lower reflectances in the blue and red wavelength region. The intensities of the reflectances varied between 0% and 3.5%. For *Elodea nuttallii* and *Najas marina*, which were in the focus of this study,
29 and 28 median spectra were calculated respectively, while for *Chara* spp. 7 and for *Potamogeton perfoliatus* 12 representative median spectra were computed. With up to 8%, the reflectance spectra of the sediments (red lines) typically showed higher intensities than the vegetation spectra. In total, 21 sediment medians were computed prior to the growing season. Comparing the sediment spectra, it can be observed that brightness decreased from the *Najas marina* site over the *Chara* spp. site, the *Potamogeton perfoliatus* site to the *Elodea nuttallii* site (Figs. 4 to 7, first plots/photos). The reason for these differences in sediment brightness might be founded in an inverse trend of the organic overlay, as an increase in organic pad decreases light reflectance. Further indicators for the presence of benthic phytoplankton were the reflectance minima at 620 nm and 680 nm. At these wavelengths, the absorption maxima of *Phycocyanin* and *Chlorophyll a* - both present in cyanobacteria - are located.

The 22 blue coloured medians of the second plots in Figures 4 to 7, represent sparsely covered sediments at the beginning of the growing season of the respective plant. Due to the necessity of cloud free conditions, it was not possible to trace different stages of density within the months of June and July.

When looking at the spectra of *Najas marina* in July (Fig. 5), exponential increases between 400 nm and 430 nm are visible. This can be attributed to the water column correction process. At this day, \(E_d\)-measurements took place at ‘0-‘ and at 4 m depth. The minor intensities at wavelengths below 400 nm and above 700 nm at 4 m (Fig. 3, right), resulted through the expression of Maritorena [1996] in a stretched shape of \(K_d\), which in turn led to exaggerations at these wavelengths. To solve such problems, the deeper \(E_d\)-measurements should be carried out at a depth of maximum 2 m. Nevertheless, the method of inverting \(K_d\) might be limited in turbid waters and when waves occur. The latter lead to a wave focusing effect, which results in high deviating \(E_d\)-measurements and therefore an unstable \(K_d\).

![Figure 4 - Sequence of remote sensing reflectances of *Elodea nuttallii* (\(R_s\); red: sediment, blue: sparse coverage, green: full coverage) from May to October and photographs of the studied population (in brackets: canopy structure).](image-url)

In case of *Elodea nuttallii* (Fig. 4), the growing season in 2011 lasted from June to October. The first spectra of a pure population were collected at the beginning of August. As long as
plants stood upright or were bent on the very top of the canopy (Fig. 4, pictures 3, 4 and 5) the spectra showed little variation. In October a noticeable change in the curvature of the reflectance spectra took place. Compared to the ones from August to September, the shape in October was more compressed and could be associated to the collapsed plants, which were not standing upright anymore, but tipped sideways (Fig. 4, picture 6). The lower ration of Chlorophyll a/Carotenoids in autumn might be the reason for the flattened trend at yellow and orange wavelengths (560 nm to 650 nm). The change from the sediment spectra (red) to the vegetation spectra (green) from May to August is well supported by Figure 4, pictures 1 to 3. A dependency of the spectral reflectances from growing depth could not be proven with our data.

The growing season of *Najas marina* (Fig. 5) lasted from July to October 2011. The spectral differences of sediment (May, red lines) and plant spectra (beginning of August, green plot) were documented as well as for *Elodea nuttallii* (Fig. 5, pictures 1 to 3). From August to October, the shapes of the curves barely changed, as the plants were standing upright and density was high all the time (Fig. 5, pictures 3 to 6). Noticeable are the two different groups of spectra, which can be recognized in September as well as in October. They might be associated with different phenological stages. As the taller growing male plants collapsed after pollination, changes in biomass and growing heights occurred. On the photographs, male and female plants cannot be separated. Again, growing depth had no influence on spectral shapes.

![Figure 5 - Sequence of remote sensing reflectances of *Najas marina* (Rs; red: sediment, blue: sparse coverage, green: full coverage) from May to October and photographs of the studied population (in brackets: canopy structure).](image)

For the *Chara* spp. test site (Fig. 6) the colonization of the bare sediment and the accompanied changes in the reflectance spectra were captured well. Due to higher and more frequent waves and cloud coverage during the month of August, only a small number of spectra could be calculated. This made it difficult to recognize or explain spectral features from the beginning of August to September. As no obvious changes in phenology or canopy structure were recognized, the varieties of the spectral shapes remain unexplained. (Fig. 6, pictures 3 to 5).
Figure 6 - Sequence of remote sensing reflectances of *Chara* spp. ($R_s$; red: sediment, blue: sparse coverage, green: full coverage) from May to September and photographs of the studied population (in brackets: canopy structure).

For *Potamogeton perfoliatus* it was most difficult to sample reflectances of the disperse population in the month of July. In case of single tall growing plants (Fig. 7, picture 2), it is difficult to collect plant spectra with a sensor which has a field of view of 7°. Hence, it is still not clear, of which component the calculated medians (Fig. 7, blue lines) are affected most; by plants, by underlying sediment or by surrounding water column. With increasing density of the population from July to end of August (Fig. 7, pictures 2 to 4), the curvatures corresponded to typical vegetation spectra (Fig. 7, plots July to end of August). Similar to *Elodea nuttallii* (Fig. 4, October plot and picture 6), the collapse of the plants in September (Fig. 7, picture 5) was represented clearly by the flattened reflectance spectra (Fig. 7, September plot). As this test site was close to the *Chara* spp. site, it was likewise affected by waves, which may explain the larger variations within the single plots.

Figure 7 - Sequence of remote sensing reflectances of *Potamogeton perfoliatus* ($R_s$; red: sediment, blue: sparse coverage, green: full coverage) from May to September and photographs of the studied population (in brackets: canopy structure).
Influences of different illumination conditions, like increasing intensities at decreasing sun zenith angles - as known from terrestrial applications - could not be identified for any of our test sites. Possibly, this effect is masked by the light scattering within the water column. Another effect, which is not investigated so far, was the presence of epiphytes and suspended solids upon the macrophytes, which affect the spectral response due to their particulate absorption spectra. However, in case of *Elodea nuttallii* epiphytes may play a minor role, as the plant is known to be allelopathic active [Erhard and Gross, 2006].

**PCA**

To discriminate a) macrophytes from bare sediments; and b) to identify macrophytes species, principal component analyses were carried out for the wavelength range between 400 and 700 nm.

The first PCA (Fig. 8) divided the medians into two clusters and one disperse group. The two clustering groups are the vegetation (green coloured) and the sediment spectra (red coloured). The third group, which is coloured blue, represents the sparse covered sediments. The dispersal of the sediments can be attributed to differences of the spectral intensities in
general and local reflectance minima, which probably arise from different organ contents or overlays. Indeed, the blue coloured spectra are widespread, but the positions of the four internal clusters (Potamogeton, Elodea/Sed_d, Charas/Sed_a and Najas/Sed_c) are defined between their associated sediment and macrophytes spectra. Depending on the density of the population at the recording time, they are located closer to the sediment or the plant group. Hence, the sparse covered populations of *Elodea nuttallii* and *Najas marina* are closer to the sediments Sed_d and Sed_c. As populations covered 50% in both cases, the higher intensities of the sediment reflectances masked the plants. The larger field of view might have increased this effect. In contrast, the coverage of 75% of the *Chara* spp. led to a position closer to the vegetation than to Sed_a. Due to the influences of the water column in case of the *Potamogeton perfoliatus* spectra, this group is similar to vegetation spectra and is therefore located close to the macrophytes cluster. The principle component 1 (PC1) described this separation with 94.8%, the second (PC2) with 2.2%, which gave a cumulative proportion of 97%.

![Figure 9 - Principal component analysis (PCA) of all medians of macrophytes between 400nm and 700nm; green: *Elodea nuttallii*, blue: *Najas marina*, red: *Chara* spp., orange: *Potamogeton perfoliatus*. The arrows indicate temporal effects; the ellipses encircle two spectral groups of *Najas marina* in September and October, respectively.](image)

The PCA for only the macrophytes from August to October (Fig. 9) showed that the two invasive species *Elodea nuttallii* (green) and *Najas marina* (blue) and the population of
Chara spp. (red) form separable clusters with only little overlaps. The dispersion of Chara spp. reflectances is caused by too small a number of measurements and/or too much noise in the measurements. The cluster of Potamogeton perfoliatus (orange) overlapped clear with the ones of Elodea nuttallii and Chara spp. The cumulative proportion of 95.5% of this PCA was reached by 90.3% of PC1 and 5.2% by PC2. By including the sampling dates (phenological stages), which are given by the month names, some overlaps can be bypassed. So for example a) Elodea nuttallii in October with Najas marina in September; b) Chara spp. in August1 within the group of others; and c) Potamogeton perfoliatus August2 within the group of September spectra of Chara spp. and Elodea nuttallii.

The dependence of the spectral shapes from phenological states of the populations is visible for Potamogeton perfoliatus and Elodea nuttallii (arrows in orange and green show the drifts). Reasons therefore might be the decreased water influence for Potamogeton perfoliatus (Fig. 7, pictures 2 to 4) and changes in the structure/pigmentation for Elodea nuttallii (Fig. 4, pictures 4 to 6). For Chara spp. no trend is visible but also not expected, as no changes in phenology were noticed. In the case of Najas marina, the specific phenology seems to become visible. A spectral grouping in September as well as in October (cf. Fig. 5, pictures 5 and 6) can also be identified in the PCA (blue ellipses). During field work it was noticed that the composition of the population had changed in favour of the female plants in the course of the month of September. Hence, the spectral differences might be due to changes in the portion of male and female Najas marina plants and the related changes in plant morphology and canopy structure of the entire population. Systematic investigations in the laboratory are necessary to verify this effect.

**Conclusion**

The study presented investigations towards coupled growth and physical reflectance models of submersed vegetation communities of the Upper-Bavarian freshwater lakes in Germany. Within the present stage, the development of spectral libraries and associated descriptive phenological libraries are in the focus. These steps are assumed to be essential with regard to a future automated mapping [Williams et al., 2003] in the frame of the envisaged monitoring system. To collect remote sensing reflectance spectra, on the basis of which the changes in phenological or structural stages of submersed macrophytes can be verified, a stable measurement set-up was developed and now introduced.

As changes in the spectral signature throughout the growing season are present, the requirement of Fyfe [2003] that spectral features need to be distinct despite seasonal variation in order to discriminate and map species is not fulfilled for our data. Hence, multi-temporal ground truth data and therefore information about the particular phenological stages area necessary to improve this process and solve problems with miss-classifications. To enable the use of a large number of remote sensing sensors, libraries of hyperspectral data is essential. For validation tasks, such data can be rescaled to all kind of spectral resolution within the given range. The use of principle component analyses allowed the differentiation of the collected spectra by species/underground.

Diurnal variations which may be up to 60% (around the green peak) are finally not discussed, but waves are assumed to have a great influence. With regard to a monitoring system the observation that with PCA even changes of such magnitude are compensated, is
the most important result. The investigation of the diurnal changes is on-going by regarding
parameters like water depth and illumination together with phenological and morphological
differences on population structure.

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