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Assessment of aerial photography as a method for monitoring aquatic vegetation in lakes of varying trophic status

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Implementation of the EU Framework Directive for Water Policy requires assessment of the ecological quality of surface waters using reliable, repeatable, quantitative and cost-effective monitoring methods. Digital colour infrared (CIR) aerial photographs representing 16 lakes of varying trophic status in the Vuoksi drainage basin, Finland, were used here to study the usefulness of remote sensing as a method for monitoring aquatic vegetation. The accuracy of the photo-interpretation method was assessed, and its ability to detect differences in the abundance of aquatic vegetation in lakes of varying trophic status was studied. Two measures of vegetation abundance based on the interpretation of aerial photographs, a colonization degree and a relative long-term change in the area of helophytes and nymphaeids, were used. The results indicated that CIR aerial photographs were suitable for mapping helophytic and nymphaeid vegetation and that the colonization degree of helophytes and nymphaeids was consistent with the nutrient content (total phosphorus and total nitrogen) of the lakes as well as with a measure of abundance based on field data.

Introduction

An urgent need for reliable, repeatable, quantitative and cost-effective methods for monitoring aquatic vegetation (macrophytes) in Europe has been created by the implementation of the EU Framework Directive for Water Policy (WFD), which is aimed at preserving and enhancing the status of water bodies, one of the main objectives being good ecological quality of surface waters all across Europe by the year 2015. Water bodies of good or high ecological quality are allowed to show only slight adverse anthropogenic impacts on their biological quality elements, i.e. phytoplankton, benthic invertebrate fauna, fish fauna, macrophytes and phytobenthos. The ecological quality of lakes is to be assessed from monitoring results which provide information on the taxonomic composition and average abundance of the aquatic vegetation, and also changes in its growth, since accelerated growth could lead to undesirable changes in the abundance of other organisms present in the water body, or to alterations in sediment or water quality (Council of the European Communities 2000). In addition to transect sampling, aerial photography is a pos-

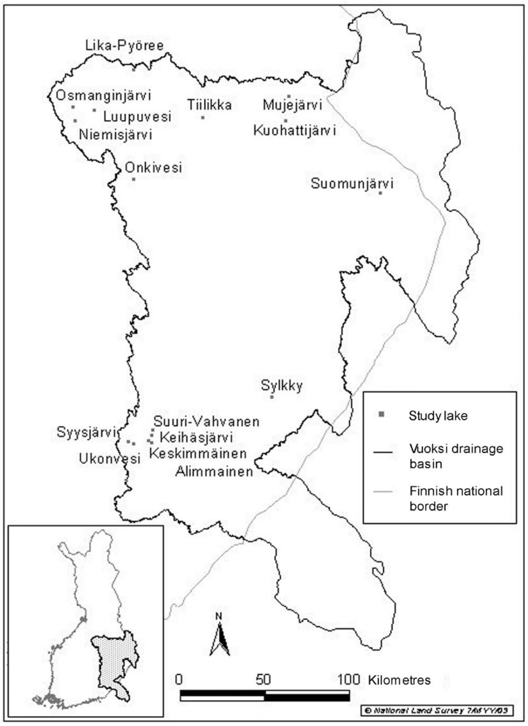

Fig. 1. Location of the lakes studied in the Vuoksi drainage basin, Finland.

sible method for monitoring aquatic vegetation and is also recognized in the WFD monitoring guidelines (Littlejohn *et al*. 2002).

Remote sensing data were used successfully in a number of studies of aquatic vegetation (e.g. Ackleson and Klemas 1987, Welch *et al*. 1988, Jensen *et al*. 1993, Marshall and Lee 1994, Malthus and George 1997, Zhang 1998, Valta-Hulkkonen *et al*. 2003b), which showed that spectrally distinct signals are governed by the density of the vegetation, the openness of the canopy, and the amounts, forms and orientations of the leaves (Penuelas *et al*. 1993, Marshall and Lee 1994, Malthus and George 1997, Valta-Hulkkonen *et al*. 2003b). Remote sensing data provide spatial and quantitative information on the aquatic vegetation, and allow geometrically rectified images to be superimposed on and compared with other geographical data in order to study temporal changes or interactions between parameters (Welch *et al*. 1988, Jensen *et al*. 1993, Lehmann *et al*. 1997, Narumalani *et al*. 1997).

The effect of lake trophic status and water quality on the species richness and abundance of the aquatic vegetation is well-known (e.g. Spence 1967, Seddon 1972, Ilmavirta and Toivonen 1986, Duarte and Kalff 1986, Rørslett 1991, Toivonen and Huttunen 1995), and the responses of the aquatic vegetation to increased productivity in lakes (eutrophication) are known to vary according to the life forms present in the vegetation. Helophytes and nymphaeids are especially abundant in small Finnish lakes under eutrophic and hypertrophic conditions (Toivonen and Huttunen 1995), and Smith and Wallsten (1986) have demonstrated in a study where the vegetation cover was analysed from aerial photographs that total nitrogen concentration is an important factor determining the percent cover of helophytes in lakes in addition to mean water depth. On the other hand, the abundance of submerged vegetation is also controlled by the transparency of the water, and the peak abundance of this life form is reached at intermediate trophic conditions with high transparency (Toivonen and Huttunen 1995). The abundance of submersed life forms can be significantly reduced under heavily eutrophicated conditions (Rørslett 1991, Toivonen and Huttunen 1995). In general, water chemistry and trophic characteristics can be used to explain differences in vegetation among lakes, whereas site characteristics explain the variability within lakes (Duarte and Kalff 1986, Hellsten 2000).

Digital colour infrared (CIR) aerial photographs were used here to test the use of aerial photography as a method for monitoring aquatic vegetation in 16 lakes of different lake type (Pilke *et al*. 2002), trophic status and anthropogenic pressures in the Vuoksi drainage basin in Finland. The accuracy of the photo-interpretation method and the ability of the method to detect differences in the abundance of aquatic vegetation in lakes of varying trophic status were assessed. Three measures of vegetation abundance were used, two based on the interpretation of aerial photographs, the colonization degree of helophytes and nymphaeids, and the relative long-term change in the area of helophytes and nymphaeids, and one based on field data, the area coverage of aquatic vegetation. As the colonization area of aquatic vegetation in a lake is dependent on the area of the depth zone suitable for the growth of vegetation, the lake morphology was taken into account when comparing the colonization areas in the lakes. The use of the colonization degree of aquatic vegetation as a biological measure of lake trophic status is also supported by its inclusion in the monitoring guidelines of the US EPA (US EPA 1998) and the WFD guidance on establishing reference conditions and class boundaries for ecological quality (Wallin *et al*. 2003). The colonization degree was defined by relating the actual area of helophytes and nymphaeids to the potential colonization area. The potential colonization area was determined using digital elevation model (DEM) and the maximum observed depth of occurrence of nymphaeid and helophytic species with the aid of a Geographical Information System (GIS) and the actual area of vegetation was based on the interpretation of the aerial photographs. The relative long-term change in the area of helophytes and nymphaeids was estimated by comparing historical aerial photographs with recent ones. The remote sensing methods used here have been reported previously in Valta-Hulkkonen *et al*. (2003a, 2003b, 2004b).

Materials and methods

The studied lakes

The 16 lakes in the Vuoksi drainage basin, eastern Finland (Fig. 1) were chosen to include lakes of different types and anthropogenic pressures. The lake types were based on the Finnish Environment Institute's suggestion for a typology of surface waters (Pilke *et al*. 2002), which categorizes lakes into ten main types. The four lake types represented here are: (1) naturally eutrophic lakes, (2) small, slightly humic lakes, (3) middle-sized, moderately humic lakes, and (4) small, very humic lakes (Table 1). One or two reference lakes of each type (representing those in a natural state) and one to five human-impacted lakes (pressures from agriculture, forestry, peat production, diffuse loading) were selected for the present study. Two areas

Table 1. Information on the lakes, the nutrient concentrations and the secchi depths are median values for the growing season in 1990–2002. *There was only one measurement for the secchi depth.

Study lake	Main pressure	Area (km^2)	Depth (m)	Total P ($\mu g\ l^{-1}$)	Total N ($\mu g\ l^{-1}$)	Secchi depth (m)
Naturally eutrophic lakes (located in nutrient rich bedrock and soil):						
Onkivesi, northern	agriculture	3.7	3.4	63	800	1.0
Onkivesi, southern	agriculture	5.4	3.4	51	655	1.1
Luupuvesi	agriculture, peat production	7.0	1.0	97	1100	0.7
Niemisjärvi	agriculture	4.2	1.5	74	1500	0.8
Osmanki	agriculture, peat production	2.8	1.2	120	980	0.8
Lika-Pyöree	a reference lake	2.0	0.6	31	660	0.9*
Small (area < 5 km^2) slightly humic (colour < 30 mg Pt l^{-1}) lakes:						
Keihäsjärvi	diffuse loading	1.4	4.0	14	460	2.3*
Keskimmäinen	diffuse loading	0.8	4.0	14	490	1.8*
Alimmainen	diffuse loading	0.7	2.4	29	640	1.9*
Syysjärvi	diffuse loading	1.8	3.3	11	450	3.0
Ukonvesi	diffuse loading	4.9	6.7	19	820	2.3
Suuri-Vahvanen	a reference lake	1.3	4.0	5	310	4.6*
Sylkky	a reference lake	1.0	3.5	8	250	5.4
Middle sized (area 5–40 km^2) moderately humic (colour 30–90 mg Pt l^{-1}) lakes:						
Kuohattijärvi	forestry	10.8	6.1	11	270	3.0
Suomunjärvi	a reference lake	6.6	5.5	8	242	2.9
Small (area < 5 km^2) very humic (water colour > 90 mg Pt l^{-1}) lakes:						
Mujejärvi	forestry	3.5	5.0	19	368	1.5
Tiilikka	a reference lake	4.2	2.4	12	300	1.8

differing in water quality, a northern and a southern area, were recognised separately for Lake Onkivesi. The trophic status of the lakes varied from oligotrophic to hypertrophic. In many of the eutrophic lakes, excessive growth of aquatic vegetation is already recognised as a problem, and some are undergoing restoration, with efforts to reduce the vegetation.

Recent aerial photograph data

The recent data available were based on digital CIR aerial photographs to a scale of 1:20 000 obtained in 2000–2002 and consisted of three wavelengths: green (500–575 nm), red (575–675 nm) and near-infrared (675–900 nm), which were separated. The aerial photographs were scanned to a ground resolution of ca. 0.5 m and both digital and manual data were used. The data acquisition is described more precisely by Valta-Hulkkonen *et al*. (2004b).

Historical aerial photograph data

The historical data were taken from black and white aerial photographs to a scale of 1:20 000 from the year 1955 and consisted of wavelengths of visible light (400–700 nm) in a single band. The photographs were scanned to a ground resolution of ca. 0.5 m and only digital data were used.

Field data

The field data were collected in July and August during the summers of 2000–2002. Reference plots and main belt transects were used for this purpose in 2001 and 2002. The reference plots were regarded as providing primary data for the remote sensing study. The plots were areas of at least 3 m × 3 m chosen from different densities of each dominant life form and species of aquatic vegetation in the lake. At least five reference plots for each dominant vegetation group were defined. The 5-m-wide main-belt transect started at the beginning of the shore vegetation and continued to the outer edge of the aquatic vegetation, or to the middle point of the lake if the vegetation extended over the entire lake. The main belt transect was divided into zones according to changes in the main life forms or species, and the frequency and coverage of each species were estimated visually on a percentage scale in each zone. The number of belt transects per lake (12–52) varied according to lake size and morphology. Both the reference plots and the main belt transects were positioned in the field using a 12-channel DGPS (Trimble GeoExplorer 3), and information on vegetation type and stand coverage, water depth and bottom type were collected in all cases. In summer 2000 also other field methods (line transects and 3 m × 3 m squares) were used and these are described by Valta-Hulkkonen *et al*. (2003b). Manual aerial photographs were used during the field survey whenever they were available. The field data were corrected differentially with the Pathfinder Office software and the correction files were imported from the base station in Evo, southern Finland (61°11´45´´N, 25°06´31´´E).

Digital image processing

Photographs or parts of photographs without strong geometric or radiometric effects, specular reflectance, relief displacement or light falloff (Ahmad and Deering 1992, Pellikka 1998, Lillesand and Kiefer 2000) were chosen for processing. In the case of the 1955 images, the effect of light falloff was normalised with the equation of Pellikka (1998). The aerial photographs were geo-referenced using Finnish digital base maps to a scale of 1:20 000. The ground resolution of the aerial photographs was increased to approximately 1.0–1.2 m from the original 0.5–0.6 m and the photographs were mosaicked when necessary. Terrestrial areas were eliminated with a mask derived from the base maps. The digital aerial photographs were interpreted with the aid of a maximum likelihood classifier, using two categories, vegetation and water, in the case of the black and white images and several categories of aquatic vegetation (up to 6 categories) for the CIR aerial photographs. The accuracies of the classified images for the years 2000–2002 were assessed by means of confusion matrices, which compare, on a category-by-category basis, the relationship between known reference data and corresponding results of an automated classification (Lillesand and Kiefer 2000). The accuracy of each vegetation category was defined by examining whether the majority of the areas of the reference plots used for the confusion matrix were classified into the right category of aquatic vegetation or not. Finally the areas of total aquatic vegetation and each vegetation category were calculated. The interpretations of the digital aerial photographs were tested in 14 lakes representing different lake types and anthropogenic pressures (Table 2). The digital image processing of the aerial photographs was performed with the Erdas Imagine image processing software.

Assessment of vegetation abundance

A Digital Elevation Model (DEM) created from digitized bathymetric maps was used to delineate the zone of suitable depth for the growth of a nymphaeid and helophytic vegetation. This zone will be referred to as the potential colonization area. The maximum observed (i.e. measured) depth of occurrence of nymphaeid and helophytic species on each lake was used as a reference in the delineation. Other factors such as bottom quality and wave exposure that have an effect on the abundance of aquatic vegetation (Duarte and Kalff 1986, Toivonen 2000, Riis and Hawes 2003) were not considered here. The classification images of aquatic vegetation representing the actual area of these life forms were superimposed on maps representing the potential colonization zone. The colonization degree of nymphaeid and helophytic vegetation was calculated and used as a measure for the abundance of the vegetation that was applicable to the naturally eutrophic lakes, middle-sized, moderately humic lakes and small, very humic lakes (Table 2). In the case of Lake Luupuvesi, the area of vegetation was analysed using a 1996 aerial photograph because active efforts have been made

Table 2. Overall accuracies of the vegetation classifications, and areas and abundance values of the aquatic vegetation. Reference lakes are indicated in italics. *Values from Valta-Hulkkonen *et al.* (2003b, 2004a). **Overall accuracy was not defined due to limited field data.

Study lake	Overall accuracy (%)	Vegetated area in 1955 (ha)	Vegetated area in 2000s (ha)	Long-term change in area of heloph. and nymph. (%)	Colonization degree of heloph. and nymph. (%)	Area coverage of heloph. and nymph. (% of area studied)
Naturally eutrophic lakes (located in nutrient rich bedrock and soil):						
Onkivesi, northern	91*	–	127*	–	46.9	–
Onkivesi, southern	82*	–	77*	–	33.4	–
Luupuvesi	80*	–	258* (355* in 1996)	–	39.6	–
Niemisjärvi	71	–	111	–	57.3	34.0
Osmanki	73	–	150	–	73.1	–
Lika-Pyöree	83	–	80	–	29.1	12.5
Small (area < 5 km^2) slightly humic (color < 30 mg Pt l^{-1}) lakes:						
Keihäsjärvi	83	4.5	22	389	–	8.4
Keskimmäinen	73	4.7	8	74	–	10.8
Alimmainen	73	2.9	13	352	–	21.6
Syysjärvi	69	7.5	25	233	–	–
Ukonvesi	82	9.5	62	553	–	–
Suuri-Vahvanen	86	3.9	8	105	–	10.1
Sylkky	100	–	12	–	–	–
Middle sized (area 5–40 km^2) moderately humic (color 30–90 mg Pt l^{-1}) lakes:						
Kuohattijärvi	100	–	42	–	9.3	16.1
Suomunjärvi	–**	–	54	–	22.7	6.2
Small (area < 5 km^2) very humic (water color > 90 mg Pt l^{-1}) lakes:						
Mujejärvi	82	–	14	–	10.3	10.0
Tiilikka	89	–	78	–	5.5	26.2

to reduce the vegetation since 1997 (including harvesting and water level regulation) and the abundance of the vegetation has significantly decreased (Valta-Hulkkonen *et al*. 2004a).

The classified images for the two years (1955 and 2002) were used to produce an estimate of the relative change in the abundance of vegetation, relating the total area of nymphaeid and helophytic vegetation in 2002 to that in 1955. This measure of abundance (the relative long-term change) was defined for the small, slightly humic lakes except for the Lake Sylkky, for which no historical aerial photographs were available (Table 2). Since no bathymetric maps were available for the lakes of this type, it was not possible to calculate the colonization degree of aquatic vegetation.

Where such calculations were possible, the resulting percentage was compared with a measure of abundance calculated from the field data by combining the frequency and coverage information from the main belt transects. This measure, known as area coverage, was calculated as:

$$\mathrm{Ac} = \sum_{i=1}^{n} \left[\frac{\sum_{i=1}^{n} \left(\frac{f_{ij}}{100} \times \frac{c_{ij}}{100} \times A_j \right)}{\sum_{j=1}^{m} A_j} \times 100 \right] \quad (1)$$

where Ac = summarized area coverage of the n species of interest (representing the percentage of the total area studied that was covered by the n species), f_{ij} = frequency estimate for species i in zone j, c_{ij} = coverage of the stand of species i in zone j, A_j = area of zone j, and m = the number of zones.

The area coverage was calculated for the entire vegetation (total species pool) and for the nymphaeid and helophytic species and was defined for two to four lakes representing each lake type considered here (Table 2). The observed total number of aquatic macrophyte species on the transects studied (including vascular plants, bryophytes and members of the *Characeae*) varied from 15 (Suuri-Vahvanen) to 41 (Syysjärvi) in the study lakes, where nymphaeids and helophytes constituted the main proportion of the total species pool (average 53.7%). All measures of vegetation abundance used here were correlated (Pearson's correlation, since the data satisfied the normality assumption) with observed trophic status as indicated by the median levels of the main nutrients (total phosphorous and total nitrogen) under the growing season in 1990–2002. The water chemistry and transparency (measured as secchi depth) data were originated from the database of the Finnish environmental administration.

Results

The digital CIR aerial photographs proved to be the most suitable for mapping the helophytes and nymphaeids, but less useful for mapping submerged vegetation. The helophytes could be divided into two main categories according to their phenotype: species with well-developed leaves, such as *Phragmites australis* Trin. ex Steud and *Carex* spp. L., and species without (or with reduced) leaves, such as *Schoenoplectus lacustris* (L.) and *Equisetum fluviatile* L. In some cases it was possible to divide these two categories further at the species or genus level. In the case of six lakes, for example, *Phragmites australis* and *Carex* spp. were classified into categories of their own. Among the nymphaeids, the *Sparganium* L. species were the only ones which could be classified to species or genus level, in the case of two lakes. In lakes with an abundant vegetation both the helophytes and nymphaeids were classified into two categories according to variations in coverage (more or less than 50%). Sparse helophytes (coverage less than 30%–50%) were combined with the categories of nymphaeids. The sparsest helophytic and nymphaeid vegetation (coverage 10% or less) merged with open water areas. The classification of submerged vegetation succeeded only in Lake Sylkky, where the isoetid *Lobelia dortmanna* L. formed a category of its own.

Assessments of the accuracy of the classifications gave values between 69% and 100% for the lakes (Table 2). The most obvious confusions were between different stand coverages of the same species group and with submerged vegetation. The total areas of aquatic vegetation in 1955 and 2000–2002 are listed in Table 2. Classification images for Lake Keskimmäinen in 1955 and 2002 are presented in Fig. 2.

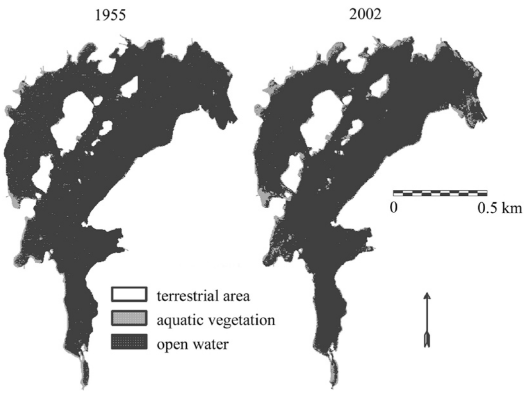

Fig. 2. Aquatic vegetation distribution maps for Lake Keskimmäinen in 1955 and 2002 (61°37´N, 27°29´E). The four aquatic vegetation categories of the 2002 classification (shore vegetation (mainly *Carex* spp.), *Phragmites australis*, dense nymphaeid vegetation and *Schoenoplectus lacustris* and sparse nymphaeid vegetation) are combined here.

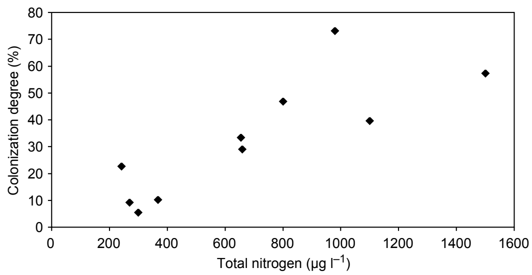

Fig. 3. Relationship between the colonization degree of helophytes and nymphaeids and water quality in the lake, indicated by total nitrogen.

The degree of colonization by helophytes and nymphaeids was markedly greater in the naturally eutrophic lakes than in the lakes of the other two types (Table 2). This measure of abundance was also greater in the human-impacted lakes than in the reference lakes, except among the middle-sized, moderately humic lakes (Table 2). The degree of colonization by helophytes and nymphaeids was positively correlated with the nutrient content in water, the lakes with higher concentrations of total phosphorus and nitrogen having a higher coverage of vegetation (Table 3 and Fig. 3).

The relative long-term change in the area of helophytes and nymphaeids was on average greater in the human-impacted lakes of the small slightly humic lake type than in the reference case, Lake Suuri-Vahvanen (Table 2). The relative long-term change was not, however, statistically significantly correlated with the nutrient content of the water (Table 3).

The degree of colonization by helophytes and nymphaeids showed a close correlation with the area coverage of nymphaeids and helophytes, but not with the area coverage of all aquatic vegetation (Table 3). The area coverage of helophytes and nymphaeids measured in the field also correlated closely with the concentrations of total phosphorus and nitrogen (Table 3). The area coverage of all species increased with water nutrient status, although the correlation was not as obvious (Tables 1–3).

Table 3. Pearson correlations of total phosphorus and nitrogen with measures of vegetation abundance. * $p < 0.05$, ** $p < 0.01$ and *** $p < 0.001$. The direction of the correlation is always positive.

		Total phosporus	Total nitrogen	Area coverage of heloph. and nymph.	Area coverage of all species
Area coverage of heloph. and nymph.	R^2	0.803	0.869		
	p	< 0.001***	< 0.001***		
	n	10	10		
Area coverage of all species	R^2	0.520	0.479	0.591	
	p	0.019*	0.027*	0.009**	
	n	10	10	10	
Colonization degree of heloph. and nymph.	R^2	0.817	0.682	0.769	0.24
	p	< 0.001***	0.003**	0.022*	0.324
	n	10	10	6	6
Long-term change in area of heloph. and nymph.	R^2	0.416	0.658		
	p	0.167	0.05		
	n	6	6		

Discussion

The digital CIR aerial photographs were used successfully for studying helophytic and nymphaeid vegetation. The classification of the aquatic vegetation was more problematic in the lakes with high than poor water transparency, however, the most obvious problem was caused by the reflectance of the sandy lake bottoms, which disturbed the classification of isoetids in particular. In one case a submerged species was recognised as a category of its own, but usually they were classified as open water. Since features of the water and lake bottom, such as water depth and colour and bottom type, have a strong effect on the discrimination of submerged vegetation, digital CIR aerial photographs cannot be regarded as a reliable method for monitoring elodeids and isoetids. These results support the authors' previous findings (Valta-Hulkkonen *et al.* 2003b) and the observations by Marshall and Lee (1994) on similar problems with submerged vegetation.

In addition to bottom reflectance, the shadows of trees on the shores disturbed the classification of the aquatic vegetation based on both the historical and recent aerial photograph data. The shadows classified as open water and, therefore, affected the total areas of aquatic vegetation. The greatest problems were experienced with the historical data, due to the low altitude angle, and in the lakes with steep elevations on the shore in the case of the recent data, as these lakes had narrow vegetation zones.

The acquisition of field data was fairly successful, but could still be developed further, since the estimation of coverage could be made more objective. The present subjectivity of the coverage estimation method was assumed to be, at least partly, the cause of the confusion between different stand coverages of the same species group in the classification. The size and number of reference plots could be increased in order to improve the confidence limits of the results, since the confidence levels of both the accuracy assessments and the classifications are dependent on the number of reference plots used in the confusion matrix. This is reflected in a fairly large difference between the minimum and maximum total accuracy values (Table 2). The total accuracy of the digital aerial photograph interpretation can be more confidently expressed as the average of all the classification accuracies, which is 82.3%. Furthermore, the classification can be performed more fluently if the person responsible for it has been involved in the field survey and consequently has prior knowledge of the features and vegetation of the lake.

The correlation between the degree of colonization by aquatic vegetation and the concentrations of total phosphorus and nitrogen in the lakes (Table 3 and Fig. 3) is in accordance with the findings of Smith and Wallsten (1986). The measure of vegetation abundance tested here treated the lake morphometry in a more detailed way than did Smith and Wallsten (1986), as the area of a suitable depth for helophytic and nymphaeid vegetation was modelled by GIS methods.

The long-term increase in the area of vegetation was great in all slightly humic lakes studied (Table 2). The long-term water quality data were insufficient to assess whether the lakes had undergone eutrophication in the long term. Even so, all the lakes can be assessed as having been more or less oligotrophic under natural conditions, based on the lake type and our knowledge on existing loading pressures. Although the change in vegetation abundance could not be attributed to the current trophic status, other factors in addition to eutrophication, such as the lowering of the water level in the 1930s in the case of Keihäsjärvi, may have accelerated overgrowth of the littoral zone in some cases (Toivonen and Bäck 1989, Toivonen and Nybom 1989). Long-term changes in the area of vegetation can therefore reflect changes in the ecological status of lakes due to anthropogenic impact more widely than is apparent in the light of changes in chemistry alone.

The confidence levels of the measures of vegetation abundance based on the aerial photographs are greatly dependent on the accuracy with which the aquatic vegetation can be classified. The most obvious sources of disturbance, bottom reflectance and shadows of trees on the shoreline, cause uncertainty in the definition of the total area of vegetation, especially in lakes with high water transparency and narrow vegetation zones. The confidence levels of the aerial photograph interpretations providing the measures of vegetation abundance could be improved by considering the vegetation coverage in the definition of its abundance. This could be done by weighting the area of aquatic vegetation by its coverage.

The colonization degree of helophytic and nymphaeid vegetation is also sensitive to the definition of the depth zone for possible occurrence of the vegetation. The GIS data used for the delineation of this zone were based on bathymetric maps of varying origin and quality, with possible errors. The definition of the maximum observed depth of occurrence may also have included some sources of error, since the depth values measured during the field survey were not related to a mean water level, as there were no data on water level fluctuations in most of the lakes. In addition other factors such as bottom quality and wave exposure that have an effect on the abundance of aquatic vegetation (Duarte and Kalff 1986, Toivonen 2000, Riis and Hawes 2003) should be considered in order to achieve a more reliable assessment for the potential colonization area.

In Finland, where the number of lakes to be monitored in accordance with the WFD is high, the costs of such surveys will be crucial, and cost-effective methods are needed. The costs of aerial photograph interpretation have been estimated to be approximately one half of those of a field survey performed by the main belt transect method (Leka *et al*. 2003). The colonization degree produced by aerial photo-interpretation is in accordance with the abundance determined from the field data and the data produced is accurate. Therefore the aerial photograph interpretation method may be applicable at least for assessing the current abundance of aquatic vegetation in a cost-effective way, and possibly it may also be used for monitoring purposes.

According to the WFD, the ecological quality of a water body subject to human impact should be evaluated using Ecological Quality Ratios (EQRs; Council of the European Communities 2000), calculated by comparing the values for biological quality elements with those for reference sites, i.e. sites with no anthropogenic stress (Wallin *et al*. 2003). This spatial approach in defining EQRs can be used in ecoregions with an adequate availability of pristine reference lakes in order to obtain reliable reference values for the biological parameters. Additional reference values for the vegetation parameters produced by the remote sensing method presented here would be needed to develop the methodology further and to assess its usefulness for defining the ecological quality of lakes.

Conclusions

CIR aerial photographs produce spatial and quantitative information on aquatic vegetation of a kind that can be acquired in a cost-effective and repeatable way. The methodology presented here proved suitable for the accurate mapping of helophytic and nymphaeid vegetation in lakes with different characteristics. Helophytes and nymphaeids were mostly classified according to life form, phenotype, and the coverage of the stands with an average accuracy for the classifications of 82%. One possible application of the aerial photograph approach would be for calculating the colonization degree of helophytes and nymphaeids. The abundance of the aquatic vegetation defined this way can be explained by current nutrient content in water, and could therefore be used to assess human impact on the ecological status of lakes in a cost-effective way.

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