

Lake catchment characteristics and external P load – cultivated area/lake area ratio as a tool for evaluating the risk of eutrophication from land use information

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The effects of land use on external P load (L_p), critical P load (L_c) and on L_p/L_c of 27 lakes in Finland were examined with regression analyses. Catchment area to lake area ratio (A_c/A_L), cultivated catchment area to lake area ratio (A_f/A_L) and the percentage of cultivated land in the catchment ($F_{\%}$) were used as independent variables. We studied whether these parameters can be used to estimate the risk of exceeding the critical P load ($L_p/L_c > 1$). All three parameters had a positive effect on L_p and L_p/L_c . Compared with A_c/A_L and $F_{\%}$, A_f/A_L had a higher coefficient of determination in predicting L_p and L_p/L_c . This was because A_c/A_L does not include land use variations in catchments and $F_{\%}$ does not include information on catchment size, while A_f/A_L includes information on both. Critical P load was exceeded when $A_f/A_L > 1.63$. A_f/A_L can be a useful and simple tool for evaluating the risk of lake eutrophication.

Introduction

Anthropogenic eutrophication is one of the most prevalent environmental problems in freshwater ecosystems (Smith 2003, Schindler 2006). In a large number of lakes, eutrophication has deteriorated the possibilities for domestic water use and recreation through its effects on water quality and biota (Carpenter *et al.* 1998). In lakes, phosphorus (P) is commonly the main nutrient limiting primary production (Schindler 1977). Therefore, controlling the human-induced external load of P to lakes is one of the main challenges in lake management.

Knowledge on the ability of lakes to withstand the external load of P is needed. Such

knowledge can be used by decision-makers (e.g. municipalities, industry or agriculture) to regulate the P load from various sources. The most widely used methods for this purpose have been the critical load model by Vollenweider (Vollenweider 1976) and its modifications (e.g. Dillon and Rigler 1974, Kirchner and Dillon 1975, Canfield and Bachmann 1981, Ahlgren *et al.* 1988). Using these models, P and chlorophyll a concentrations of lakes are predicted using lake characteristics, such as mean depth and water residence time, with data on P load. Additionally, many dynamic phosphorus models were developed (Ahlgren *et al.* 1988, Janse *et al.* 2010). In general, all models are sensitive to uncertainties in external load values (Reckhow 1979, Janse

et al. 2010). This is a challenge especially in catchment areas where diffuse P load dominates. Compared with point load, for example from industrial, municipal and wastewater treatment plants, the estimation of diffuse load is more problematic (Carpenter *et al.* 1998). This is a severe problem because diffuse load from agricultural and forestry areas is also more difficult to control than point load and it has nowadays become the dominant component in regulating the external load and water quality of numerous lakes (Soranno *et al.* 1996, Carpenter *et al.* 1998, Palviainen *et al.* 2015). Therefore, several attempts have been made to predict nutrient load and water quality from land use information (Dillon and Kirchner 1975, Reckhow *et al.* 1980, Johnes 1996, Soranno *et al.* 1996, Ekholm *et al.* 2000, Tong and Chen 2002, Nielsen *et al.* 2012). Such models often become complicated because they should include numerous parameters such as soil type, catchment slopes, livestock numbers, crop types and human population data (Meeuwig and Peters 1996, Ekholm *et al.* 2000, Bennion *et al.* 2005, Arhonditsis *et al.* 2007). Models often require so extensive input data, that they may be unsuitable for end-users performing risk assessment in practice (Heckrath *et al.* 2008). Therefore, many attempts were also made to provide simple, user-friendly tools for assessing P load from catchments with limited data (Heckrath *et al.* 2008). These indices typically account for both source and transport factors and they are used to assess where P leaching occurs in the catchment (Sharpley *et al.* 2001, Veith *et al.* 2003, Heckrath *et al.* 2008).

In the present study, we aimed to develop a simple tool to assess the risk of exceeding the critical P load of lakes. We explored the possibility to combine the critical load concept and the catchment land use information in a novel way. We hypothesized that it is possible to use the coverage of cultivated land in the catchment to estimate the risk of exceeding the critical P load. This can be possible, as the effect of cultivated land on the external nutrient load often dominates compared with other forms of land use (Ekholm *et al.* 2000, Reed-Andersen *et al.* 2000, Bechmann *et al.* 2003). We tested a new approach by relating the area of cultivated land in square kilometers to the area of the recipient

lakes. If the predictive value of the new approach is high enough, the method could be used in planning the land use in catchments. Our tool was compared with a previously used catchment area–lake area relationship and percentage coverage of cultivated land in the catchment.

Materials and methods

Data were collected from 27 lakes in Finland (Table 1). The lakes were chosen randomly among those where suitable data (P load measurements based on discharge and P concentration measurements and thus independent on land use information) were available. The trophic state of the lakes varied from mesotrophic to hypereutrophic, lake area from 0.3 km² to 155 km² and lake mean depth from 1.2 m to 20.8 m (Table 1). The catchment area (A_C) of the lakes (lake excluded) varied between 1.1 km² and 896 km² (mean 179 km²) and percentage of cultivated and pastured land together ($F_{\%}$) in the catchments between 5% and 31%. For $F_{\%}$, cultivated areas dominated with a mean coverage of 16% while the coverage of pastured areas averaged only 0.1%. The lake percentage ($L_{\%}$) in catchment areas varied between 0% and 7.9% (Table 1). To avoid the scale effect, the mean catchment area (excluding the lake) in the present dataset was 179 km². The load of total P concentration (P_{tot}) per unit catchment area may decrease with increasing catchment area, but this phenomenon is significant only for catchments < 20 km² (Prairie and Kalff 1986, Ekholm *et al.* 2000). In the present dataset, 5 out of 27 lakes had a catchment area smaller than 20 km².

The nutrient load entering lakes is usually dependent on the relationship between A_C and the lake area (A_L). The higher the catchment area in relation to the lake area (A_C/A_L), the higher the nutrient load per unit area of the lake (e.g., Kalff 2003). On the other hand, land use in the catchment has an effect on nutrient leaching and $F_{\%}$ has often been used to characterize the load from catchments (Rekolainen 1989, Ekholm *et al.* 2000). $F_{\%}$ reflects the nutrient load from the catchment, while A_C/A_L gives an impression on the overall load entering the lake (Rekolainen 1989, Ekholm *et al.* 2000).

Because A_C/A_L does not account for land use variations between catchments and $F_{\%}$ does not include information on catchment size, we combined the information given by these two parameters. A_C and $F_{\%}$ were combined to create a new parameter, A_F/A_L , which gives the cultivated area in the catchment (A_F) in relation to the surface area of the lake:

$$A_F/A_L = [(A_C \times F_{\%})/100]/A_L. \quad (1)$$

The effect of A_C/A_L , $F_{\%}$, and A_F/A_L on external P load (L_p) and on the ratio of L_p and critical P load (L_C) was studied with linear regression analysis. The data were ln-transformed data to improve normality. If the studied catchment parameters have a significant effect on L_p/L_C , their values leading to $L_p/L_C > 1$ can be considered critical for the lake. The coefficient of determination (R^2) obtained from the regres-

sions were also used to evaluate the relationships between catchment characteristics and P load (Nielsen *et al.* 2012). The catchment area of each lake, and the land use in the catchment was determined with the VALUE tool provided by the Finnish Environment Institute (<http://paikkatieto.ymparisto.fi/value>). The tool derives land use variables and lake percentages taken from Coordination of Information on the Environment (CORINE 2012) land cover data. The national CORINE 2012 database for Finland has a spatial resolution of 25 m. $F_{\%}$ and A_F/A_L included areas that were defined by the CORINE data as cultivated land or pasture. The values of L_p and water discharge (q_s), as well as total P concentrations (P_{tot}) were obtained from the HERTTA database of the Finnish Environment Institute (<https://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp>) and from the reports of the local environmental authorities (Table 2). For

Table 1. Characteristics of the study lakes and their catchment areas. The lake is not included in its catchment area.

Lake	Location	A_L (km ²)	Mean depth (m)	Max depth (m)	A_C (km ²)	$F_{\%}$	$L_{\%}$
Bodominjärvi	60°15'13"N, 24°40'17"E	4.1	4.3	12.7	27.3	19	2.0
Enäjärvi	60°20'17"N, 24°21'38"E	4.9	3.2	9.1	29.1	22	0
Harvanjärvi	63°63'69"N, 27°57'33"E	2.1	3.9	15.2	7.1	13	0
Hiidenvesi	60°22'30"N, 24°11'31"E	30.3	6.7	33.0	896.0	16	5.7
Hirvijärvi	60°40'4"N, 24°37'41"E	4.3	14.0	29.6	22.0	10	2.3
Jalanti	61°9'32"N, 23°45'4"E	6.4	2.7	6.1	740.0	19	5.1
Karhujärvi	60°13'32"N, 24°16'55"E	1.9	2.2	4.9	228.0	15	6.7
Katumajärvi	60°59'19"N, 24°31'3"E	3.8	7.1	18.9	44.2	8	6.7
Kymijärvi	60°58'12"N, 25°47'56"E	6.5	2.6	11.0	34.0	6	6.5
Kynnäröjärvi	61°7'24"N, 24°59'25"E	0.3	1.3	3.0	28.0	26	0.5
Köyliönjärvi	61°6'58"N, 22°20'53"E	12.5	3.0	12.8	133.0	30	0
Loppijärvi	60°41'26"N, 24°25'27"E	11.8	1.8	6.7	70.0	14	1.5
Matalajärvi	60°15'1"N, 66°24'41.54"E	0.7	1.2	2.4	3.8	17	0.0
Nuutajärvi	61°02'6"N, 23°27'25"E	1.8	1.9	2.3	87.0	17	4.4
Oksjärvi	60°79'58"N, 23°94'56"E	3.1	2.6	7.0	14.0	5	1.2
Parkanonjärvi	61°59'2"N, 23°1'65"E	4.7	6.8	22.0	707.0	7	7.0
Pusulanjärvi	60°27'28"N, 23°58'51"E	2.1	4.9	10.6	221.0	15	7.9
Puujärvi	60°15'15"N, 23°42'58"E	6.4	8.3	21.7	21.0	15	2.3
Pyhäjärvi, Orimattila	60°42'46"N, 26°0'14"E	12.9	20.8	68.0	445.0	31	3.2
Pyhäjärvi, Säskylä	60°59'20"N, 22°18'8"E	155.0	5.5	26.2	451.0	21	0.1
Rusutjärvi	60°42'72"N, 24°97'99"E	1.3	2.5	3.6	3.3	24	0
Savijärvi	60°21'36"N, 25°20'5"E	0.4	1.6	2.6	1.1	15	0.3
Tiiläänjärvi	60°32'26"N, 25°42'11"E	2.1	4.4	10.3	36.0	22	2.1
Tuusulanjärvi	60°26'34"N, 25°3'37"E	5.9	3.2	10.0	83.0	28	0.9
Villikkalanjärvi	60°46'3"N, 26°2'14"E	7.1	2.9	8.9	404.0	31	1.2
Vuonisjärvi	63°8'41"N, 30°6'7"E	0.7	1.5	5.3	20.0	11	1.5
Äimäjärvi	61°3'14"N, 24°9'51"E	8.5	2.9	9.0	85.0	13	2.5

most lakes, the values of q_s included direct measurements from lake inlet streams, while for some of the lakes, q_s was calculated based on reported water retention time and lake volume. Values for L_p were calculated using water discharge data and P concentration measurements using an approach most suitable for lakes with the given number of available observations (Jones *et al.* 2012). The P load from the catchments accounted also for the contribution from unmonitored areas by areal extrapolation (Ekholm *et al.* 1997, Tammeorg *et al.* 2017). The number of L_p estimates varied lake to lake and mostly covered several recent years with monthly measurements. The critical P load (L_c) is determined by the relationship of lake mean depth and water residence time, or by the relationship of inflow water discharge and lake area; termed as areal water load, q_s (e.g., Brett and Benjamin 2008). In this study, L_c ($\text{mg P m}^{-2} \text{ a}^{-1}$) was calculated as:

$$L_c = 0.174q_s^{0.469}. \quad (2)$$

The equation (Vollenweider 1976, as cited in Eloranta 2005) has frequently been used in estimating the critical load of Finnish lakes (e.g., Karvonen 2007, Hagman 2011, Pulkkinen 2014). L_p was expected to increase with increasing A_c/A_L and A_f/A_L . On the other hand, L_c increases with increasing A_c/A_L , because q_s usually increases and water residence time decreases with increasing A_c/A_L . Therefore, to explore the factors determining the effect of A_c/A_L , $F_{\%}$ and A_f/A_L on L_p/L_c , their relationship with q_s of the studied lakes was studied by linear regression analysis. Since lake area (A_L) is included in L_c , A_c/A_L and A_f/A_L , regression analysis was used to explore whether A_L had any effect on L_p/L_c . To track the possible scale effect among the studied catchments, the relationship between catchment area and L_p per unit catchment area (L_p divided by the area of the catchment) was also analyzed with regression analysis. Additionally, the relationship of the percentage coverage of lakes ($L_{\%}$) and L_p/L_c was studied with regression analysis. This was done because lake coverage can substantially affect the retention of nutrients in the catchment areas (e.g., Röman *et al.* 2018).

Results

The external P load (L_p) of the lakes varied between $25 \text{ mg m}^{-2} \text{ a}^{-1}$ (Puujärvi) to $5200 \text{ mg m}^{-2} \text{ a}^{-1}$ (Jalanti), with the mean value being $1065 \text{ mg m}^{-2} \text{ a}^{-1}$ (Table 2). The epilimnetic concentration of P_{tot} ranged from $9 \mu\text{g l}^{-1}$ to $114 \mu\text{g l}^{-1}$ (mean $53 \mu\text{g l}^{-1}$) with the lowest and highest values occurring in Hirvijärvi and Matalajärvi, respectively (Table 2). The critical P load (L_c) varied between $166\text{--}1058 \text{ mg m}^{-2} \text{ a}^{-1}$ (Table 2). L_p exceeded L_c in 17 out of 27 lakes.

All the three studied catchment parameters, $F_{\%}$, A_c/A_L and A_f/A_L , had a significant effect on L_p (Fig. 1). The coefficient of determination was the highest with A_f/A_L and the lowest with $F_{\%}$ (Fig. 1). All three parameters had also a significant effect on L_p/L_c (Fig. 2). The coefficient of determination was again the highest with A_f/A_L and the lowest with $F_{\%}$ (Fig. 2). According to the regression equation between A_f/A_L and L_p/L_c , the external load exceeded the critical load (L_p/L_c) when $\ln(A_f/A_L) > 0.49$; i.e., when $A_f/A_L > 1.63$ (Fig. 2). The threshold value of $F_{\%}$ was 12.9%.

The areal water load, q_s , was dependent on A_c/A_L ($F_{1,25} = 145.12$, $R^2 = 0.85$, $p < 0.001$) and A_f/A_L ($F_{1,25} = 108.18$, $R^2 = 0.81$, $p < 0.001$), while the effect of $F_{\%}$ on q_s was insignificant ($F_{1,25} = 1.15$, $R^2 = 0.04$, $p = 0.293$). $L_{\%}$ had no effect on L_p/L_c ($F_{1,25} = 0.42$, $R^2 = 0.02$, $p = 0.521$). Neither did lake area A_L have any effect on L_p/L_c ($F_{1,25} = 0.67$, $R^2 = 0.02$, $p = 0.419$). External P load per unit area of the catchment was not dependent on the catchment size ($F_{1,25} = 0.95$, $R^2 = 0.04$, $p = 0.337$). A_f/A_L and $F_{\%}$ had a significant relationship with the epilimnetic P_{tot} concentration in the lakes while there was only a marginal effect of A_c/A_L on P_{tot} (Table 3).

Discussion

Corroborating previous studies, the results demonstrated that the external P load of lakes (L_p) increased with increasing A_c/A_L (Kortelainen 1993, Kalff 2003). A_f/A_L had a strong effect on L_p and a higher coefficient of determination than A_c/A_L . This was because the values of A_c/A_L included all land use types, most of which have a weaker effect on P load than agricultural areas.

For instance, forests covered 29–78% of the catchment areas included in A_C/A_L . Vuorenmaa *et al.* (2002) estimated that the mean specific load of P from agricultural areas was $110 \text{ kg km}^{-2} \text{ a}^{-1}$, which was 12 times the load from forested areas ($9 \text{ kg km}^{-2} \text{ a}^{-1}$). Similarly, Rekolainen (1989) has reported that P load from agricultural catchments varies from $90\text{--}180 \text{ kg km}^{-2} \text{ a}^{-1}$ in Finland, which is about ten times higher than the value from forested land. A_F/A_L included only cultivated and pastured areas, therefore it had a closer relationship with L_p than A_C/A_L . $F_{\%}$ was also a significant predictor of L_p . The coefficient of determination

was, however, clearly lower with $F_{\%}$ than with the other two parameters, because $F_{\%}$ does not take the catchment area into consideration.

The load of P_{tot} per unit catchment area tends to decrease with increasing catchment size (Ekholm *et al.* 2000). With the present dataset, such phenomenon was not detected. This was probably because the scale effect was strong especially in smaller catchments than most of those used in this study (Prairie and Kalff 1986, Ekholm *et al.* 2000). $L_{\%}$ had no effect on L_p/L_C , although the nutrient retention in the catchment area usually increases with increasing cover-

Table 2. The ratio of cultivated area in the catchment and lake area (A_F/A_L), external P load (L_p), critical P load (L_C), L_p/L_C ratio, areal water load (q_s) and concentration of total phosphorus in the epilimnion (P_{tot}) of the study lakes. Sources of the L_p , q_s and P_{tot} values for each lake are given below the table.

Lake	A_F/A_L	L_p ($\text{mg m}^{-2} \text{ a}^{-1}$)	L_C ($\text{mg m}^{-2} \text{ a}^{-1}$)	L_p/L_C	q_s (m a^{-1})	P_{tot} ($\mu\text{g l}^{-1}$)
Bodominjärvi ^{1,2}	1.26	507	258	1.97	2.3	32
Enäjärvi ^{1,3}	1.26	323	313	1.03	3.5	98
Harvanjärvi ^{1,4}	0.46	73	166	0.44	0.9	20
Hiidenvesi ^{1,5}	4.71	924	481	1.92	8.7	70
Hirvijärvi ^{1,6}	0.52	57	203	0.28	1.4	9
Jalanti ^{1,7}	22.07	5200	914	5.69	34.3	63
Karhujärvi ^{1,8,9}	18.12	4232	920	4.60	34.9	72
Katumajärvi ^{1,10}	0.96	232	313	0.74	3.5	19
Kymijärvi ^{1,11}	0.31	48	232	0.21	1.8	24
Kyynäröjärvi ^{12,13}	28.64	2263	878	2.58	31.6	50
Köyliönjärvi ^{1,14}	3.18	710	304	2.34	3.3	83
Loppijärvi ^{1,15,16}	0.82	93	183	0.51	1.1	30
Matalajärvi ^{1,17}	1.07	338	276	1.23	2.7	114
Nuutajärvi ^{1,7}	7.59	2700	317	8.52	3.6	110
Oksjärvi ^{1,18}	0.22	70	209	0.33	1.5	12
Parkanonjärvi ¹⁹	11.06	2128	1058	2.01	47.0	30
Pusulanjärvi ^{1,20}	15.96	1707	916	1.86	34.5	49
Puujärvi ^{1,12}	0.49	26	188	0.14	1.2	12
Pyhäjärvi, Orimattila ^{1,21}	10.61	814	523	1.56	10.5	44
Pyhäjärvi, Säkylä ^{1,22}	0.61	106	224	0.47	1.7	17
Rusutjärvi ^{1,23}	0.61	254	338	0.75	4.1	60
Savijärvi ^{1,24,25}	0.41	260	252	1.03	2.2	80
Tiiläänjärvi ^{1,12}	3.76	1428	431	3.31	6.9	80
Tuusulanjärvi ^{1,26,27}	3.94	960	358	2.68	4.7	101
Villikkalanjärvi ^{1,28}	17.71	2302	671	3.43	17.8	111
Vuonisjärvi ^{1,29}	3.34	783	635	1.23	15.8	54
Äimäjärvi ^{1,30}	1.32	283	282	0.81	2.8	42

¹HERTTA database (2015) ²Hagman (2010), ³Taponen (1997), ⁴Kauppinen (2007), ⁵Hagman (2012), ⁶Salo & Harjula (2012) ⁷Närinäen *et al.* (2002), ⁸Valjus (2011), ⁹Valjus (2012), ¹⁰Juttila and Salminen (2006), ¹¹Järveläinen *et al.* (2012), ¹²Tammeorg *et al.* (2017), ¹³Kaipainen *et al.* (2002), ¹⁴Paloheimo (2010) ¹⁵Keto and Sammalkorpi (2009), ¹⁶Aaltonen and Juttila (2006), ¹⁷Karvonen (2007), ¹⁸Mäkelä (2016), ¹⁹Skippari *et al.* (2003), ²⁰Lappalainen (1998), ²¹Hämeen vesienhoidon toimenpideohjelma (2015), ²²Ventelä *et al.* (2007), ²³Huuhko & Hanski (2013), ²⁴Hagman (2011), ²⁵Riihimäki (2008), ²⁶Muukkonen (2010), ²⁷Ojanen (1979), ²⁸Knuutila *et al.* (1994), ²⁹Tossavainen (2014), ³⁰Kontio (2011)

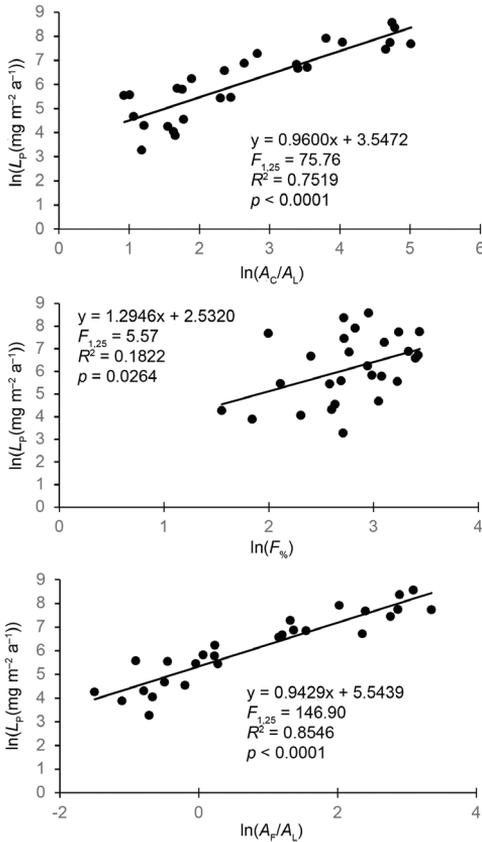


Figure 1. The effect of A_C/A_L (top), $F_{\%}$ (middle) and A_F/A_L (bottom) on external P load (L_p) of the study lakes. The values are ln-transformed.

age of lakes (Ekholm *et al.* 2000, Rantakari *et al.* 2004, Mattsson *et al.* 2005, Röman *et al.* 2018). This was attributed to the relatively low $L_{\%}$ values in the studied catchments. The mean $F_{\%}$ of the catchments was 17.5%. According to the regression equation presented by Rekolainen (1989), such field coverage results in a P load of 34 kg km⁻² a⁻¹. This was in good accordance with the estimated average P load entering our study lakes per unit area of the catchments (40 kg km⁻² a⁻¹).

A_C/A_L , A_F/A_L and $F_{\%}$ had a significant effect on the L_p/L_C ratio. Thus the risk of exceeding the critical P load could be predicted with all three parameters. There are, however, several aspects that have to be taken into account. Together with their effect on L_p , A_C/A_L and A_F/A_L have an influence on L_C . This is because A_C/A_L is usually negatively correlated with the water residence

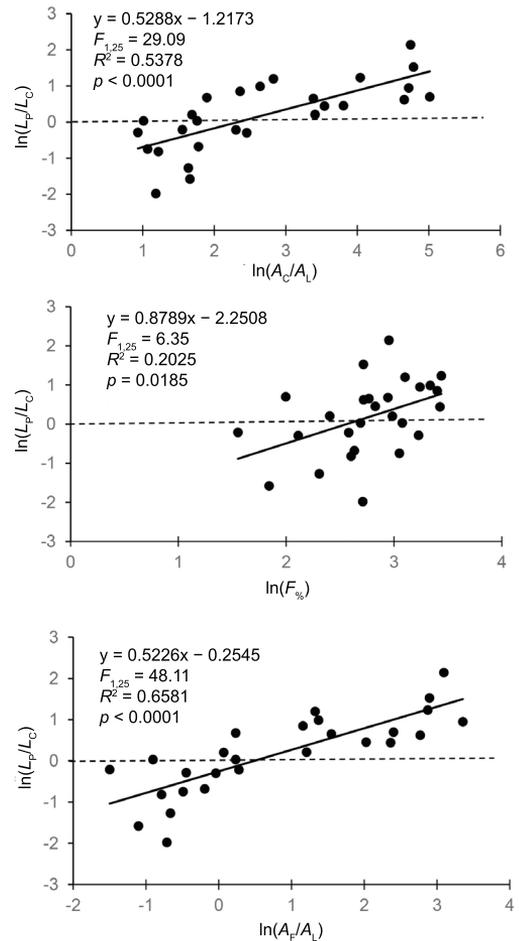


Figure 2. The effect of A_C/A_L (top), $F_{\%}$ (middle) and A_F/A_L (bottom) on L_p/L_C . The dotted horizontal line shows the level where $L_p = L_C$. The values are ln-transformed.

time of lakes (Algesten *et al.* 2003, Kalff 2003). Accordingly, both A_C/A_L and A_F/A_L had a significant effect on q_s . Since L_C increases with increasing q_s , the effect of A_C/A_L and A_F/A_L on q_s attenuated their effect on L_p/L_C . When using A_C/A_L , it must also be considered that the catchment areas of inflowing streams are often used in areal extrapolation to estimate the water discharge and load from unmonitored catchments (Ekholm *et al.* 1997).

When predicting L_C , A_C/A_L had a higher coefficient of determination than A_F/A_L . For L_p , on the other hand, A_F/A_L had a higher coefficient of determination than A_C/A_L . These findings suggested that the leaching of P in relation to water

Table 3. Results from the regression analyses on the relationship of $F_{\%}$, A_C/A_L and A_F/A_L with L_C and epilimnetic P_{tot} concentration. The statistics are for ln-transformed values and statistically significant p -values are bolded.

Independent variable	Critical P load (L_C)			
	Regression equation	$F_{1,25}$	R^2	p
A_C/A_L	$y = 0.3936x + 4.8671$	145.49	0.85	< 0.001
$F_{\%}$	$y = 0.2425x + 5.2491$	1.15	0.04	0.294
A_F/A_L	$y = 0.3458x + 5.6336$	108.32	0.81	< 0.001

Independent variable	Epilimnetic P_{tot}			
	Regression equation	$F_{1,25}$	R^2	p
A_C/A_L	$y = 0.2117x + 3.2123$	4.17	0.14	0.052
$F_{\%}$	$y = 0.9473x + 1.1654$	15.93	0.39	< 0.001
A_F/A_L	$y = 0.2760x + 3.5506$	10.71	0.30	0.003

discharge increases more strongly with increasing A_F/A_L than with increasing A_C/A_L . This was explained by concentration differences. Water discharging from cultivated areas usually shows considerably higher concentrations of P compared with waters coming from areas with different land cover such as forests (Ekholm *et al.* 2000, Vuorenmaa *et al.* 2002).

When $F_{\%}$ was used as the predictor of L_P/L_C , the regression had a steeper slope but a lower coefficient of determination than with A_C/A_L or A_F/A_L . The steeper slope was explained by the insignificant effect of $F_{\%}$ on q_s and consequently, a weak effect on L_C . On the other hand, $F_{\%}$ does not account for the variability between the lake area and the catchment area, which resulted in a large variation and low R^2 value in the regression between $F_{\%}$ and L_P . In the present dataset for instance, Villikkalanjärvi and Pyhäjärvi (Orimattila) had a similar $F_{\%}$ in their catchments (31%) and almost similar catchment area. However, L_P/L_C was 3.43 for Villikkalanjärvi and 1.56 for Pyhäjärvi. This was because the area of Villikkalanjärvi was considerably smaller than that of Pyhäjärvi. Thus, although the catchments had the same percentage of cultivated land, A_F/A_L was considerably higher for Villikkalanjärvi (17.7) than for Pyhäjärvi (10.6). Due to the strong effects of cultivated areas on P load, this led to different L_P/L_C values.

A_F/A_L and $F_{\%}$ had a significant relationship with the epilimnetic P concentration amongst the study lakes, but A_C/A_L did not; which again high-

lighted the strong effect of agriculture on P load. The regressions for P concentration had considerably lower R^2 values than the regressions for external P load. This was expected, because compared with nitrogen and carbon concentrations in lakes, a smaller part of the variation in P concentration can be explained by catchment characteristics (Rantakari *et al.* 2004). P concentration in the water column is strongly regulated by numerous in-lake factors. Internal P load (i.e., recycling of P from the sediment to the water column) is an important water quality regulator in a large number of lakes (e.g., Søndergaard *et al.* 2003, Tammeorg *et al.* 2017). The intensity of internal P load is governed by numerous lake characteristics such as water depth, wind exposure, aquatic vegetation and activities of the biota (Horppila and Nurminen 2003, Søndergaard *et al.* 2003, Mazutski *et al.* 2007). Therefore, P concentration in the water often fluctuates independently on external P load. Consequently, when internal P load dominates, the Vollenweider (1976) model can fail in predicting the water quality (Ahlgren *et al.* 1988, Brett and Benjamin 2008).

The effect of internal P load could also be seen when comparing lake P concentrations and predictions on external P load (L_P). Critical P load (L_C) was exceeded when $A_F/A_L > 1.63$. This was the case in 13 out of the studied 27 lakes. The average P_{tot} concentration of these lakes was $71 \mu\text{g l}^{-1}$. Of the 14 lakes with $A_F/A_L < 1.63$, the mean P_{tot} concentration was $41 \mu\text{g l}^{-1}$. In

three of these lakes (Savijärvi, Matalajärvi and Enäjärvi), P_{tot} concentration was considerably higher than on average in this group of lakes. For Matalajärvi and Savijärvi, this was explained by their low mean and maximum depths. In shallow lakes, internal load due to sediment resuspension is often intensive and the effect of internal load on nutrient concentration is strong, because the sediment surface:water column ratio is high (Søndergaard *et al.* 2003). Therefore, land use is a better water quality predictor for deep lakes than for shallow lakes (Nielsen *et al.* 2012). Accordingly, earlier studies in Matalajärvi and Savijärvi have indicated that the recycling of P from the sediment to the water column is very intensive (Mykkänen 2007, Lappalainen *et al.* 2013). Enäjärvi has a long history of intensive internal P load, which is due to the low P-binding capacity of the sediment (Salonen *et al.* 1993, Varjus 2015). If Matalajärvi, Savijärvi and Enäjärvi were excluded, the average P_{tot} concentration in the lakes with $A_F/A_L < 1.63$ was $25 \mu\text{g l}^{-1}$, which was close to the $20 \mu\text{g l}^{-1}$ concentration threshold set by the Vollenweider (1976) model for lakes where $L_p < L_C$.

The present results suggested that if the aim is to assess the risk of exceeding the critical P load of a lake, A_F/A_L can be a better predictor than $F_{\%}$. The relationship between A_F/A_L and L_p/L_C was strong despite many factors excluded from the analysis. The slopes of the fields, soil texture and farm management practices can have a considerable impact on the P load from cultivated land (Johnes 1996, Ekholm *et al.* 2000, Kyllmar *et al.* 2006). Such data are required for accurate load estimates. The present results demonstrated, however, that if data for more complicated models are not available, A_F/A_L can be used as a simple tool to assess the risk of exceeding the critical nutrient load of lakes. Due to the simplicity of the approach, single A_F/A_L threshold values, such as 1.63 (calculated based on the present data) can probably be applied only for relatively restricted group of lakes. However, regional variability is a common phenomenon in models using land use data (Rantakari *et al.* 2004) and the threshold values have to be separately evaluated for each dataset. The results suggest that the estimated threshold can be applied to catchments with $F_{\%}$ varying from 5–31%

and $L_{\%}$ (lake excluded) from 0–7%. Catchments having very different $F_{\%}$ and $L_{\%}$ than those used in the present study likely have different nutrient retention capacities and A_F/A_L thresholds. For lakes that have important sources of point load, the A_F/A_L tool must be applied with caution. In spite of this, A_F/A_L is a promising and simple, user-friendly tool for evaluating the risk of lake eutrophication based on land use information.

Conclusions

Our results showed that catchment area to lake area ratio (A_C/A_L), cultivated catchment area to lake area ratio (A_F/A_L) and percentage of cultivated land in the catchment ($F_{\%}$) can be used to predict the risk of exceeding the critical P load. However, A_F/A_L had the best predicting power. This was because it contained information on both land use and catchment area variations. Using the data of 27 lakes located in southern Finland, we showed that critical P load was exceeded when $A_F/A_L > 1.63$. A_F/A_L can be a useful simple tool for evaluating the risk of lake eutrophication.

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