Uncertainty in paired-catchment studies – does nitrogen export increase after forest drainage?

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Summary
Paired-catchment studies are used to quantify the effect of land management on nutrient export to water bodies. In these studies, a treatment effect is represented as a difference between the observed and estimated 'natural state' exports. The 'natural state' export is calculated using a regression model between the nutrient exports from control and from treatment catchments for the pre-treatment dataset. The uncertainty in the pre-treatment regression is usually ignored. We examined how this uncertainty was reflected in the treatment effects of forest drainage on nitrogen export in two paired catchments in eastern Finland. The results indicate that uncertainty in the paired-catchment analysis has important implications to the interpretation of the result.

Key index words: ditching, nitrogen, paired catchment, water protection

Introduction
Forest drainage increases nitrogen (N) export to brooks, rivers, and lakes. The effect of drainage on nutrient export is typically investigated using paired catchment experiments (Ahtiainen and Huttunen, 1999; Åström *et al.*, 2001). The catchments in the experiment should be relatively similar in terms of area, topography, geology, and vegetation to justify the basic assumption that the catchments response identically to manipulations (Cosby *et al.*, 1996). One of the catchments is ditch drained after a pre-treatment period. A relationship between the nutrient load from the control and from the treatment catchments is calculated by regression analysis (Grip, 1982; Neal, 2002; Nieminen, 2004). For the post-treatment period, the regression model and the load from the control catchment are used to predict the load for the treatment catchment under the assumption that the treatment has not occurred (Scott, 1999; Watson *et al.*, 2001). The difference between the observed and predicted loads is assumed to be a measure of the treatment effect (Watson *et al.*, 2001). The total treatment effect is calculated by summing up the post-treatment differences over the period when the difference is greater than zero (Grip, 1982; Ahtiainen and Huttunen, 1999).

In paired catchment studies uncertainty in the relationship between the loads from the control and from the treatment catchments for the pre-treatment period is typically neglected and the post-treatment predictions for the treated catchment are produced assuming that the regression model is free of uncertainty (Grip, 1982; Rosén *et al.*, 1996; Reynolds *et al.*, 1995; Ahtiainen and Huttunen, 1999; Scott, 1999; Joensuu *et al.*, 1999; Nieminen, 2004). This is problematic, because the higher is the uncertainty - described in terms of variance in regression coefficients and residuals (Searle, 1997) – the less reliable is the regression prediction for the post-treatment period. Finally, the ignored uncertainty is transferred to the estimates of treatment effect, which can easily result in false conclusions.

The objective is to study treatment effects on nitrogen loads and account for the uncertainty in the pre-treatment dataset in analysing two sets of paired catchment data from eastern Finland. We investigate how uncertainty is propagated to estimated treatment effect of forest drainage.

Materials and methods

The paired catchment experiments
Koivupuro (treatment catchment, area 118 ha), Suopuro (treatment catchment, area 113 ha) and Välipuro (control catchment, area 86 ha) are situated in Sotkamo, eastern Finland (63°52'N, 28°39'E). The altitude of the catchments varies from 200 to 220 m a.m.s.l. and long-time (1971-2000) mean annual precipitation and air temperature are approximately 560 mm and 1.9 °C, respectively (Drebs *et al.*, 2002). The share of peatlands is 57 % in Koivupuro, 70 % in Suopuro, and 56 % in Välipuro. The bedrock consists of gneiss granite and granodiorite. In Koivupuro, 32 ha of the area was ditch drained in 1983, 6 ha was clear-cut in 1983, 4 ha was mounded and ditched in 1986 and 6 ha was fertilised in 1989. In Suopuro, 15 ha of the area was ditch drained with protective zones in 1983.

Nitrogen load

V-notch weirs were installed in catchment outlets, where water level was recorded continuously. The daily runoff series were derived based on the water level measurements and the stage-discharge relationship of the weir. Runoff at the measurement weir was sampled 1-2 times per month for chemical analyses of water quality (Ahtiainen and Huttunen, 1999). The concentration of total nitrogen (N) was determined from unfiltered water samples colorimetrically after oxidation with peroxodisulfade and reduction in a Cd–Cu column.

The daily concentration of N was interpolated from the measured discrete values and daily N loads were calculated as a product of measured daily runoff and estimated daily concentration. The results until 1994 have earlier been published in Ahtiainen and Huttunen (1999) without considering the effects of uncertainty.

Data analysis

Propagation of uncertainty from the pre-treatment dataset to the estimation of treatment effect can be quantified using the following linear regression analysis.

$$T_i = a_0 + a_1 C_i + b_1 I_1 + b_2 I_2 + b_3 I_3 + \ldots + b_m I_m + e_i,\ i=1,2,3,\ldots n. \quad \text{(Eq. 1)}$$

where

- i is the year index and n is the total number of years in the dataset,
- T_i is the observed annual N load for the treatment catchment (kg ha^{-1} a^{-1}) in year i,
- C_i is the observed annual N load in control catchment (kg ha^{-1} a^{-1}) in year i,
- k is the post-treatment year index, k = 1,2,3,…m and m is the number of years in the post-treatment period,
- I_k is a dummy variable for post-treatment years, if year i $=j+k$ then $I_k=1$, else $I_k = 0$
- j is the number of years in the pre-treatment period,
- a_0, a_1, b_1, b_2,…,b_m are the regression coefficients, and
- e_i is the error term.

In the analysis uncorrelated errors (e_i) with homogeneous variance were assumed. The degrees of freedom of the error term depend on the number of pre-treatment years (df = j-2), but it does not depend on the number of post-treatment years (m). Estimates for the parameters a_0 and a_1 do not depend on post-treatment loads T_i, $i>j$. Estimates for the coefficients b_1, b_2,…,b_m represent annual treatment effects, and cumulative treatment effect is obtained as sum $b_1+b_2+\ldots+b_k$.

Results

In both of the studied catchment pairs, ditching increased significantly the N export to watercourses. In Suopuro, where ditching with water protection had been carried out, the increase in N load, i.e. the treatment effect, was statistically significant for three years after the drainage, and the maximum annual treatment effect was 0.5 kg ha^{-1} (Fig. 1, Table 1). In Koivupuro, where water protection measures were not conducted, the treatment effect was significant for four years, and the maximum annual treatment effect was 1.5 kg ha^{-1}. After these periods, the treatment effects were masked

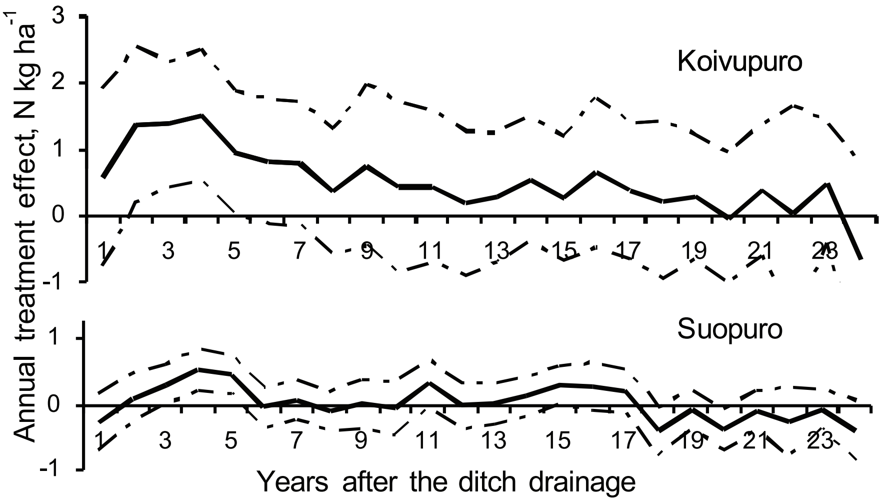

Figure 1. Treatment effects (solid lines) from paired catchment experiments where the treatment catchment has been ditched without water protection (Koivupuro) and with water protection (Suopuro). The dashed lines represent 95 % confidence limits for the treatment effect that are affected by the uncertainty in the pre-treatment dataset.

Table 1. Parameter estimates and goodness of fit measures affected by the pre-treatment datasets in Suopuro and Koivupuro paired catchments: constant (a_0) and slope (a_1) (Eq. 1) and their standard errors (SE), standard error of estimate (SEE), and R^2. Parameter estimates for the treatment effects ($b_1 \ldots b_m$) and their confidence limits are presented in Fig. 1.

Model	a_0 (SE)	a_1 (SE)	SEE	R^2
Suopuro	-0.281 (0.141)	0.933 (0.090)	0.061	0.998
Koivupuro	-0.471 (0.446)	1.070 (0.285)	0.192	0.990

by the uncertainty originating from the pre-treatment dataset. There is no unambiguous method for determining the duration of the treatment effect. A number of years when the treatment effect is significant can be used as an estimate for the minimum duration of the treatment effect. However, the actual duration may be longer, since the experimental set-up is insufficient to detect small differences. The maximum duration of the treatment effect can be gained as a number of years at the point where the cumulative treatment effect reaches the maximum value. The maximum cumulative treatment effect (2.2 kg ha^{-1}) was reached in Suopuro 17 years after the ditching. In Koivupuro, several treatments have been carried out during the monitoring period and the cumulative treatment effect increases till the end of the period. The cumulative treatment effect in the end of the period was in Koivupuro is 13.2 kg ha^{-1}.

Conclusions

Consideration of uncertainty in the pre-treatment dataset should be included in the paired catchment studies in order to avoid biased estimates of the management effects on the loads. This consideration is important even though the goodness of fit in the regression models is high. The smaller the treatment effect the more relevant is the consideration of uncertainty in the pre-treatment dataset. In order to detect small treatment effects of light methods of forest management and water protection measures, it is necessary to improve the measurement accuracy in paired catchment experiments.

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