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Influence of climate change on nutrient flows in boreonemoral floodplain ecosystem

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Abstract

In boreal and boreonemoral zones the weather conditions play an essential role in nutrient flows in rural landscapes. Winter and summer have been the most stable seasons with respect to nutrient losses and changes in processes affecting nutrient release. On the contrary, spring and autumn are associated with generally high nutrient losses due to peak flow, and determine in large scale the character of physicochemical and biological processes also for summer and winter, respectively. The following factors have the highest priority in weather-induced changes in nutrient fluxes: a) duration of frozen surface, b) snowpack peak water, c) precipitation pattern over warm period, d) duration and continuity of certain weather, e) occurrence of night frost events, f) number of soil freeze-thaw cycles.

Two GCM models (HadCM2 IS92a and ECHAM3TR IS92a) were used to estimate potential climate change. The results show that temperature rise is associated mainly with the cold season and significant changes are expected in precipitation pattern. However, the main weather types will remain the same as nowadays but will have different duration and frequency of occurrence.

Climate change scenarios show that both annual polarisation of nutrient flow and the share of irregular short-term nutrient fluxes will increase compared to the present situation in the boreonemoral floodplain. The main share of nutrient losses will occur in October-April and summer will replenish only with small losses.

1 Introduction

Changes in nutrient fluxes in agricultural landscapes have often been explained by land use intensity and structure, whereas climatic parameters have been handled as a necessary addition to water balance calculations. Analyses carried out in recent years show greater impact of weather conditions on material fluxes in the landscape than was presumed earlier [1, 2, 3, 4]. Weather influence on nutrient losses has been found to be the higher the smaller and the more uniform is the catchment [5].

Interannual and seasonal variations in nutrient losses are very high in the boreal and boreonemoral zone where weather variability is high. Typical meteorological variables, such as monthly mean air temperature and precipitation do not describe well enough the annual course of nutrient flows in association with weather conditions. Climatic seasons are distinguished according to strict criteria as qualitatively different periods [6]. Every season is expected to have its specific complex of weather types, atmospheric circulation, direction of weather change, etc. Climatic seasons begin at different times and have different duration every year, depending on weather conditions. In long-term the starting date and duration of certain climatic seasons reflect climate change. Relationship between climatic seasons (set of weather types) and nutrient runoff can be used to predict pattern of nutrient losses under climate change.

Simple statistical models based on random discrete sampling data do not describe well enough nutrient losses in small catchments [7, 8]. The random discrete sampling strategy normally used for monitoring purposes underestimates P loss by more than 50% because most of the P loss occurs during storm events [3]. For predictive models it is very important to follow certain critical periods when biological and chemical processes are switched from one type to another or hydrological characteristics are rapidly changing.

This paper examines in depth the effects of different weather types and meteorological characteristics that influence nutrient fluxes in small river catchment and especially in floodplain areas. On the background of monitoring the nutrient loss in the Sipe River catchment, seasonal variation and processes leading to nutrient release are studied in detail.

2 Material and methods

2.1 Study area

The Sipe River catchment is situated in South Estonia, 10 km south-east of Tartu. This is a typical small river drainage area within the South-East Estonian moraine plain with undulating orography and numerous dissecting primeval valleys. Dominant soils are planosols, podzols and podzoluvisols which are mainly in agricultural use, while gleysols and histosols predominate in valleys.

The Sipe River catchment lies at 60–100 m a.s.l. Relative height of landforms remains mostly between 5–15 m. The area studied in detail lies on the upper course of the river in a small branch of the primeval valley. The orography of the

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area clearly defines the watershed boundary and main flow paths through different vegetation and land-use units. Stream discharge consists of base flow originating from groundwater and outflow from the lake adjacent to the study area. During droughts no water discharge from the lake may occur.

The relative height difference of the valley in the area of detailed study is 11 m. Slopes achieve usually 3–8°, in some sections exceeding 15°. The bottom of the valley is occupied by floodplain meadow. Clay substrate underlying the wetland results in a shallow perched water-table, poorly drained and highly organic soils, and reduced inputs of regional groundwater. The depth of organic sediments in the floodplain area is up to 6 m, in most of the area still remaining between 2 and 4 m. The deepest layers include also gyttja.

Dominant vegetation patterns in the floodplain meadow consist of *Carex*, *Filipendula*, gramineous plants, *Geranium*, *Anthriscus*, *Urtica* and *Salix*.

2.2 Sampling and data

2.2.1 Water sampling

Water sampling wells on the Sipe River floodplain constitute an almost regular grid. The sampling wells were located at a distance of 100–200 m from one another along the river and at 15–90 m across the river. Exact location of the sampling wells was determined upon features such as the vegetation pattern, soil properties and hydrological conditions.

Surface and subsurface water quality sampling oriented to weather type is used instead of traditional random sampling. Use of process-oriented sampling is based on the assumptions that (i) weather conditions can be classified, (ii) they have different frequency of occurrence, and (iii) all weather types result in different intensity of material flow. The intensity of both vertical flow (leaching) and horisontal flow (overland, subsurface and groundwater flow) varies. The intensity of material flow is unique for any vegetation/landscape unit. Taking water samples simultaneously from wells situated in different vegetation types, the influence of certain weather conditions and climatological seasons can be distinguished.

A total of 16 main weather classes were distinguished based on climatological seasons. During these weather conditions, on a day characteristic of the determined meteorological situation, water samples were taken for chemical analyses (TIN, P_{tot}, NO_3^-, NO_2^-, NH_4^+, PO_4^{3-}, SO_4^{2-}, Fe, Ca, Al, K, Mg) and the following water parameters were measured: water level, temperature, O_2, pH, redox potential (ORP), electric conductivity and salinity. The full set of chemical analyses of water samples was taken also for any extreme weather event (e.g. drought, intensive rainfall, long rainy period, etc.) during early stage, maximum extent and end of the event.

Intensive observations with a 3-hourly interval were used to determine short-term changes in physicochemical parameters in surface and groundwater and their response to meteorological phenomena in different phases. Intensive observations lasted one to three weeks in a row and this enabled to estimate the daily course of water parameters in three weirs on the river and in all sampling wells. Water level, temperature, O_2, pH, ORP, electric conductivity and salinity were measured. The water samples were chemically analysed (parameters as listed above) 1-3 times during intensive observations.

2.2.2 Vegetation pattern

Large-scale vegetation patterns and land-use types were identified from digital aerophotographs taken in two different seasons according to vegetation aspects. More exact borders of vegetation patterns and small-scale patches were determined using a tachymetric survey. Vegetation patterns mapped by tachymetric survey according to dominant/indicator species was carried out at scale 1:1000 and it covers the whole study area.

2.2.3 Meteorological data

Meteorological measurements were carried out by an automatic weather station GroWeather located in the middle of the detailed study area in the floodplain meadow. Meteorological parameters were registered with 1 hour interval. The measured parameters were: minimum, maximum and average air temperature (°C); soil temperature (°C at 10 cm depth); intensity of solar radiation (W/m^2); solar energy (Ly); air pressure (mb); wind speed (m/s); maximum wind speed (m/s); wind direction (°); wind chill (°C); precipitation (mm); precipitation intensity (cm/hour); relative humidity (%) and dew point (°C).

Long-term time series analyses are based on data from the Tartu meteostation of the Estonian Meteorological and Hydrological Institute located 9 km NW.

2.3 Climate change models

HadCM2 and ECHAM3TR General Circulation Models were selected for Estonian Country Case Study on Climate Change Impacts and Adaption Assessments and used also in this study. The models were selected based on the resolution, in accordance with precipitation data and giving preference to a more recent model if otherwise equal [7].

HadCM2 - Hadley Centre, UK, 1994-95, resolution 2.5 × 3.75, transient, mean monthly precipitation pattern correlation coefficient 0.77.

ECHAM3TR - European Centre, Hamburg, 1995, resolution 2.8 ×2.8, transient, mean monthly precipitation pattern correlation coefficient 0.67.

The former, developed by Hadley Centre, UK, indicates a rather moderate increase in air temperature and precipitation while the latter, ECHAM3TR, predicts significant warming and growth of precipitation.

Three alternative greenhouse gas emission scenarios developed by IPCC were used: (i) IS92a – the IPCC medium emission scenario, (ii) IS92c – the IPCC lowest emission scenario, (iii) IS92e – the IPCC highest emission scenario. All IPCC scenarios may be regarded as reference scenarios that describe how future greenhouse gas emissions might evolve in the absence of climate policies beyond those already adopted.

ForHyM was used to calculate values for annual evaporation rates, snowpack accumulations and mean soil moisture contents under different climate change scenarios [8].

3 Results and discussion

Application of GCM with different climate change scenarios gives good bases for general conclusions on potential dynamics of nutrient flows as the model estimates include annual dynamics of air temperature, precipitation, cloudiness, wind speed and water vapour field with monthly resolution. This is sufficient to describe changes in the duration of snow cover, snow pack, evapotranspiration or river runoff and main part of nutrient losses. In several cases nutrient flows are described by short-term fluxes [3] caused by particular weather events which is not described by GCM.

In long-term weather prediction the method of historically analogous years is widely used. In climate research this method is adapted by classifying a longer time series to groups of years by temperature (very cold, cold, medium, warm), precipitation (humid, medium, dry) or other parameters and investigating meteorological parameters separately by different groups. Similar methods are applicable to study influence of climate change on nutrient flows. Different years are divided into climatological seasons and numerous weather events that result in clearly defined nutrient fluxes. Despite of climate change all main weather types and climatological seasons will remain the same as nowadays but will have different duration and frequency of occurrence. Integrating all nutrient fluxes that take place during defined climatological seasons and unregular but countable weather events we can decide about nutrient flows under climate change by means of historically analogous years.

3.1 Long-term trends in time series and predicted changes in climate

Two scenarios, HadCM2 IS92a and ECHAM3TR IS92a were used as basic, also calculations for the extremal versions (HadCM2 IS92c and ECHAM3TR IS92e) were carried out to estimate the variability of results. As seen in Fig. 1, the variability is moderate [11]. The figure shows clear and obvious trends: snow packs will decrease and snowmelt will occur earlier with climate warming. Reduced influence of snowmelt on stream discharge will increase the synchronisation between precipitation and stream discharge. Higher cyclonic activity in the Northern Atlantic brings during cold period of year more frequent inflow of warm Atlantic air masses. This will lead to less stable weather with more frequent storms and melting periods in winter. Due to less snowpack, shorter duration of snow cover and frequent melting periods the peak flow and floods in early spring will be less intensive. Base flow, typical for summer, will be reached earlier and will last until September when significant increase of river runoff will set in because of higher precipitation. For the growing period, soils will become slightly drier.

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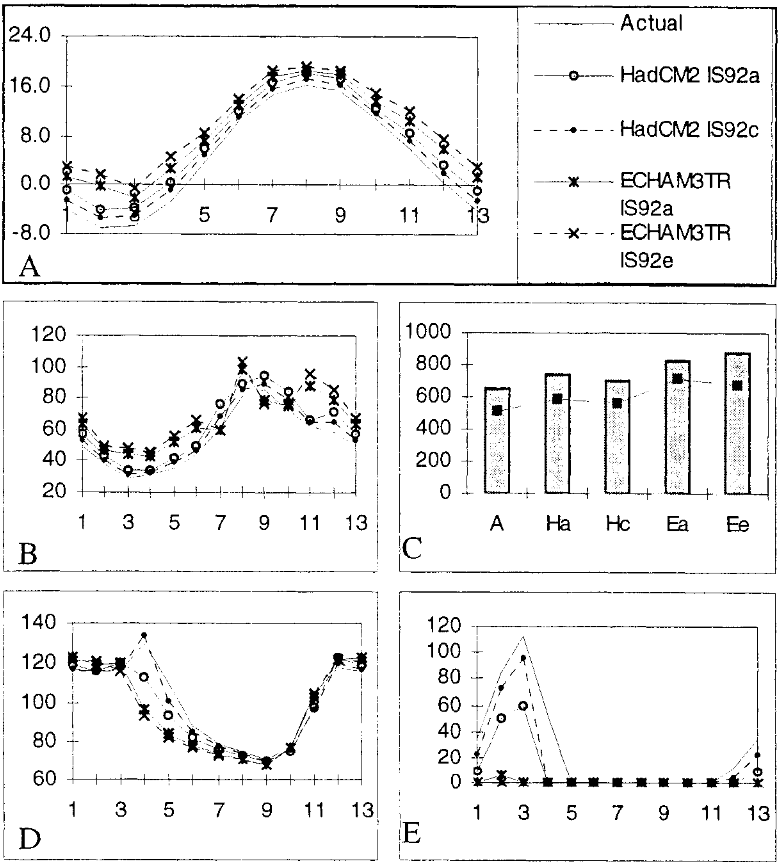

Figure 1: Annual variability of monthly mean temperature (°C) (chart A) and precipitation (mm) (chart B) at spruce forest site on fertile soils according to the four chosen scenarios as compared to actual data (climate as today preserved for the upcoming century). ForHyM calculated annual variability of monthly mean soil moisture content (mm) (chart D), annual evapotranspiration (line) compared to annual precipitation (mm) (columns on chart C) and water content in snowpack (mm) (chart E) for the four scenarios and actual conditions.

Increased drought stress may occur, since the scenarios lead to drier spring and slightly drier summer. Decrease in soil moisture content is relatively low for Estonia. Mean annual groundwater level will not change significantly but seasonal variation is expressed by water level rise in autumn, winter and spring by 10-20 cm. Main factors supporting increased groundwater recharge in winter will be the higher air temperature, precipitation reaching to ground as rain and unfrozen soil. In summer groundwater level drops by 30 cm.

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In general the time series analyses follow the same tendencies as shown by GCM. Mean annual air pressure shows a weak rising trend which is statistically not significant. Mean annual air pressure has significantly lowered in the last 25 years. In summer air pressure shows stronger rising trend and has weak negative trend in autumn and winter. Mean monthly air temperatures show no clear trend in summer, but temperature increase is significant in January, February, March and in less extent also in autumn. Mean annual and monthly precipitation are highly variable but have weak rising trend with clear cycles of 50-60, 25-30 and 5-7 years [6]. For last decades precipitation shows decreasing tendency in summer and rising trend for winter.

3.2 Nutrient fluxes under certain weather conditions and climatic seasons

Long-term monitoring of nutrient runoff in the Sipe River catchment shows clear annual course with peak flow in early spring, high nutrient losses also in autumn, and the lowest nutrient runoff in summer (TIN 0.01-0.4 kg ha^{-1} $month^{-1}$ and P_{tot} 0.0001-0.01 kg ha^{-1} $month^{-1}$). Low temperature, thick snowpack (>20 cm), frozen surface and low water discharge are the main factors that keep nutrient losses at a low level during the winter period. The highest interannual variability of nutrient losses is associated with autumn (TIN 0.01-1.6 kg ha^{-1} $month^{-1}$ and P_{tot} 0.003-0.02 kg ha^{-1} $month^{-1}$), variability is high also in late winter and spring (TIN 0.02-1.3 kg ha^{-1} $month^{-1}$ and P_{tot} 0.001-0.04 kg ha^{-1} $month^{-1}$).

3.2.1. Response of nutrient fluxes to irregular weather events

The highest nutrient fluxes are associated mainly with precipitation events which form floods or surface flow. Long-lasting rainy periods result in the increase of water-table and uniformly high water runoff with low TIN concentration (3-3.5 mg l^{-1}) but significantly higher P_{tot} concentration (0.06 mg l^{-1}) while due to continuously high runoff the nutrient losses are high. According to climate change projections amount of precipitation increases, also long rainy periods in spring and autumn become more frequent. In beginning and end of vegetation period nutrient uptake by plants is low and therefore both nutrient concentration and losses during long rainy periods will increase.

High nutrient losses occur also during short intensive rainfalls (P>10 mm) when nutrient concentrations are very high (TIN 6-7 mg l^{-1}, P_{tot} 0.8-1 mg l^{-1} , 2-2.5 times the average). Number of short intensive rainfall events is expected to double due to climate change, no change in nutrient concentration is foreseen. This phenomen will contribute to nutrient runoff in higher amount but because of limited infiltration of intensive rainfall water impact to water chemistry of subsurface- and groundwater is low as mainly surface flow is formed.

Nutrient losses from subsurface and deeper layers of floodplain depend highly on dissolved O_2 concentration, ORP and water level. The lowest O_2 and ORP values are observed in winter when surface has been frozen for long period or in warm summer months with little precipitation. In winter the water level is normally high (0-20 cm below ground level) while water level is the lowest in summer (50-110 cm below ground level), leading to low-lying stagnant

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groundwater. In periods of very low ORP higher Al and Fe runoff is observed. ORP values of about half of the annual mean typical for particular vegetation pattern lead to increase in Al losses 2–4 times (up to 0.89 mg/l) of the mean annual Al runoff. Fe concentrations were under the same conditions about twice as high (3.38 mg/l) as the annual mean. Main sulphur release is explained by decomposition and mineralization processes, but severe very intensive short-time sulphate fluxes in case of very low ORP in summer indicate possible sulphate reduction. No significant correlation between sulphate losses and Al, Fe fluxes is found until ORP value below –100 mV. Milder climate with higher precipitation rate predicted by GCM calculations brings to potential decrease in material fluxes which are dependent on ORP value (Al, Fe, SO_4, PO_4) as period of frozen surface with limited water and gas exchange will be minimal or absent. On contrary, higher evapotranspiration, lower water level, and high temperature will result in much higher fluxes in summer, especially when long dry period is followed by intensive rain, and steep increase in the concentration of SO_4 (from 8 to 50 mg/l), P_{tot} (from 0.03 to 0.1 mg/l) and NO_2 (from 0.005 to 0.05 mg/l).

Very important factor affecting nutrient fluxes is soil freeze–thaw cycle. Short-term freeze–thaw cycles in autumn promote N_2O fluxes, especially the first one. The freeze–thaw cycle increased denitrification and nutrient release in the whole floodplain meadow but the magnitude of release varied in different sites and vegetation communities. The highest response was given by the *Carex* community (increase of NO_3-N from 0.005 to 1.49 mg l^{-1} and P_{tot} from 0.028 to 0.059mg l^{-1}), where due to a high water-table level the ice formation probably disintegrated aggregates more effectively. A short but high NO_3 flux was characteristic also for the *Salix* forest (NO_3-N from 0.005 to 1.09 mg l^{-1}), while the response in the *Filipendula* community was similar in extent but with longer time lag. Total-P is less influenced by frost. The freeze–thaw cycle strongly influences also cation fluxes resulting in a pulse-like behaviour. The strongest pulse is triggered by the first strong night frost episode or frost period, the following freeze–thaw cycles induce gradually weaker fluxes, until the surface freezes in winter and the next strong pulse takes place in spring. According to climate change predictions first freeze–thaw cycle will delay about 1 month. Milder winter means that more freeze–thaw cycles will occur instead of 105 day period of frozen surface currently. Thereby nutrient flows caused by freeze–thaw cycles will have significantly higher occurrence, especially when freeze–thaw cycle is associated with rainfalls (as modelled by GCM).

3.2.2 Relation between nutrient flows and climatic seasons

According to linear trend during the period of 1891-1998 climatic seasons have significantly changed ($p < 0.05$). Summer (11 days), autumn (5 days), early winter (18 days), and late winter (7 days) have become longer. Decrease of spring (3 days) and late autumn (9 days) is not significant, but decrease of winter (30 days) is significant even at $p < 0.01$ level [12]. The change will continue with climate change and will bring to higher instability of weather due to intensive cyclonic activity in Northern Atlantic. In winter it will cause frequent thaw periods of 1-2 weeks which highly alterate surface- and stream-water chemistry, leading to higher N and particulated-P losses. According to ECHAM3TR scenarios winters in present sense will disappear being replaced by early and late winter. In the floodplain meadow in spring when the groundwater level is close to surface and both soil matrix and macropore transmissivity are exceeded, overland flow occurs. It leads to high nutrient losses but rather low variation in stream water chemistry where the concentrations remain 4–5 mg/l for TIN, 0.03–0.06 mg/l for P_{tot} and 2–10 mg/l for SO_4.

In summer the nutrient concentration and runoff in a floodplain meadow are determined mainly by the water-table level. In wet summers when precipitation from May to September exceeds 500 mm and the water-table level is only 0–35 cm below the ground level, the nutrient concentration is spatially relatively uniform (1–2 mg/l NH_4, 2–4 mg/l TIN, 0.02–0.05 mg/l PO_4) but nutrient loss is high due to intensive subsurface flow and high water discharge. In dry summers when precipitation is less than 150 mm in May - September and the water level is more than 50 cm below the ground level, spatial variation in nutrient concentration is high. Compared to interannual mean value the concentrations of TIN, NO_2, K and P_{tot} are in dry summer lower while those of Mg, Ca, NH_4, Fe and Al have a tendency to increase. A dry summer followed by intensive rainfalls and rapid increase in the water-table level results in steep increase in the concentration of SO_4 (from 8 to 50 mg/l), P_{tot} (from 0.03 to 0.1 mg/l) and NO_2 (from 0.005 to 0.05 mg/l). A tendency to increasing concentration is shown also by NO_3, TIN, PO_4 and Ca. Mg and Al show no clear trend, the concentration of Fe is slightly decreasing but clearly lowering concentrations after rainfalls are characteristic for K (from 15 to 5 mg/l). Changes in Mg and K concentration are mainly due to dilution. Changes in different nitrogen forms indicate highly intensified denitrification which benefits (especially after long drought) of infiltrating precipitation and changes in O_2, ORP and humidity. Denitrification fluxes remain high also in late autumn.

4 Conclusions

In the boreal zone weather has its main influence on nutrient flows through the cold season. The duration of snow cover, frozen surface and snowpack determine the extent of the peak flow with high nutrient loss in early spring. Increase of air temperature in winter will reduce snowpack and duration of period with frozen surface. Therefore infiltration will increase and compensate higher evapotranspiration in summer.

Spatial differences in the water and nutrient runoff are the smallest at the highest saturation of soil matrix and when the overland flow makes a large contribution to the discharge. With a decrease in soil saturation the areal contrast in nutrient concentration is increasing. However, high water-level results in an intensive subsurface and overland flow with high nutrient runoff. The lower is the water-table the higher is the nutrient turnover within the floodplain meadow and the lower is the nutrient loss by discharge.

Climate change scenarios show that both annual polarisation of nutrient flow and share of irregular short-term fluxes will increase compared to present situation in the boreonemoral floodplain. Main nutrient losses will occur in October-April and summer replenishes only with little nutrient losses.

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