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Carbon, nitrogen and phosphorus cycling in river marginal wetlands; a model examination of landscape geochemical flows

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Abstract. The importance of landscape geochemical flows was investigated using a dynamic model simulating carbon, nitrogen and phosphorus cycling in riverine wetlands, which has been described in a previous paper. The hydro-geomorphic unit (HGMU) concept was incorporated in the model by defining a separate, complete unit-model for each unit (HGMU) within the wetland. These unit-models were connected by defining the flows of nitrogen and phosphorus between them. These flows, also called landscape geochemical flows, usually consist of flows of water containing N and P.

The model was applied to a site at Kismeldon Meadows, in south-western England. This site consists of two units, a slope and a floodplain, separated by a ditch, which catches most of the run off and shallow groundwater flows from the slope. Only an estimated 1% of the N and P that leaves the slope unit in the water outflow reaches the floodplain unit; the rest is caught in the system of ditches, which prevent the geochemical flows taking their natural course. To examine the influence of this system of ditches, the model was run for the same site, but without the ditches. This is comparable to a situation of a restored site, where run off and shallow groundwater flows containing nutrients, can freely get from the slope to the floodplain.

The computer simulation experiment reconnecting the slope and floodplain showed that this (1) increased the nutrient input into the floodplain, causing a higher biomass production, and (2) increased the wetness of the floodplain, causing slower decomposition, which together (3) led to a faster soil organic matter accumulation in the floodplain. Nutrient inflows became relatively more important compared to atmospheric deposition, especially for phosphorus. By connecting the slope and the floodplain more nitrogen and less phosphorus flowed into the river.

1. Introduction

River marginal wetlands are often complex aggregations of landscape components with different geomorphology, hydrology, land use and vegetation.

The term hydro-geomorphic units (HGMUs) (Maltby et al. 1994) has been adopted for such components in this study. Arranged along elevational gradients from uplands to river, these units often exchange water and dissolved and particulate matter through run-off and groundwater discharge phenomena. During the passage through the units, these substances become part of the complex biogeochemical processes within the units, which may lead to chemical transformations with important consequences for the ecological functioning of the units. Actions (e.g., heavy fertilization) in one unit may strongly affect the productivity and nutrient cycling of another. A complicating factor in the analysis of these interactions is that the landscape has often been modified by man e.g., to improve drainage or prevent flooding. As a result original pathways may have been blocked or flows may have been short-circuited to the lower unit or the river itself.

It is necessary to study the biogeochemical flows between as well as within the units to obtain insight into the effects of interactions among units for their biogeochemical functioning, and for the functioning of the landscape as a whole. The classification proposed by Kozlovskiy (1972) is a useful way to identify and appreciate the importance of the various flows.

According to Kozlovskiy, flows of elements through the landscape can be divided into three categories. Firstly, mainly vertical flows from soil to plants and animals, and back to the soil form the so-called main migrational cycle (MMC). Secondly, landscape geochemical flows (LGF), which are usually parallel to the earth's surface. These flows enter and leave landscape prisms with a direction that can depend on the season, weather conditions or gravity. The third category are extra landscape flows (ELF), which can be positive or negative. Positive ELF's are inputs into the landscape and accumulate. They can enter the landscape unit through the atmosphere or, for instance, through groundwater flows. Negative ELFs are outputs from the landscape unit, e.g., erosion. Koslovskiy expected that the MMC is quantitatively much more important than LGF or ELF, as has indeed been demonstrated for forested catchments (Bormann & Likens 1979).

Studying the biogeochemical behaviour of landscape units is very important in the framework of the development of environmental policies. Many landscapes in agricultural regions are being enriched with nutrients. Hydrological landscape flows lead to movement of nutrients downslope, which is a potential hazard for semiterrestrial and aquatic systems such as wetlands, streams and rivers. The nutrient source-sink relationships of the various landscape units, their spatial arrangement and degree of connectivity will determine to a large extent whether nutrients will flow quickly into streams, or are retained in landscape units upslope. In many landscapes, hydrological shortcuts, e.g., drainage ditches, are present which have strongly accelerated the outflow of water and nutrients from the (often fertilized) upland landscape units.

This paper describes a modelling approach to study the biogeochemical interactions among units in a river corridor landscape, i.e., Kismeldon in Devon, England. This site consists of a floodplain of the River Torridge and a sloping area, which is separated from the floodplain by a system of ditches. The slope and the floodplain are considered separate units. The processes of the MMC are modelled for each unit separately using a dynamic model simulating carbon, nitrogen and phosphorus cycling, described earlier (Van der Peijl & Verhoeven 1999). LGF's are modelled by addition of a hydrologic flow model to the original model. The ELF's, mainly atmospheric deposition, denitrification and volatilization, are modelled as part of the unit models.

The questions addressed in this paper are:

(1) Which transfers of N and P occur between the slope and floodplain units in Kismeldon Meadows, and are these of potential significance for the (long-term) functioning of the slope (nutrient losses) or floodplain (nutrient gains)?
(2) What is the quantitative importance of the LGF or ELF relative to the MMC (for N and P) in river corridor wetlands?
(3) Which transfers of N and P would occur if the original connection between the two units, which was interrupted by the construction of a ditch at the lower end of the slope, would be restored?

2. Methods

The model developed by Van der Peijl and Verhoeven (1999) was applied by determining relatively homogeneous areas within the heterogeneous landscape, using the hydro geomorphic unit (HGMU) approach (Maltby et al. 1994, 1996). A separate (unit)-model was made for each HGMU and these areas were connected through hydrological flows, which contained nutrients (Figure 1). This way the model could account for spatial differences as well as landscape geochemical flows. To describe the hydrochemical flows a hydrological sub-model was added to the unit-models.

2.1 *The model for one unit*

The model (Van der Peijl & Verhoeven 1999) is a dynamic simulation model that consists of different sub-models of C, N and P dynamics that have the same basic structure. The model has 24 variables, six of which are in the carbon sub-model, nine in the nitrogen sub-model and nine in the phosphorus

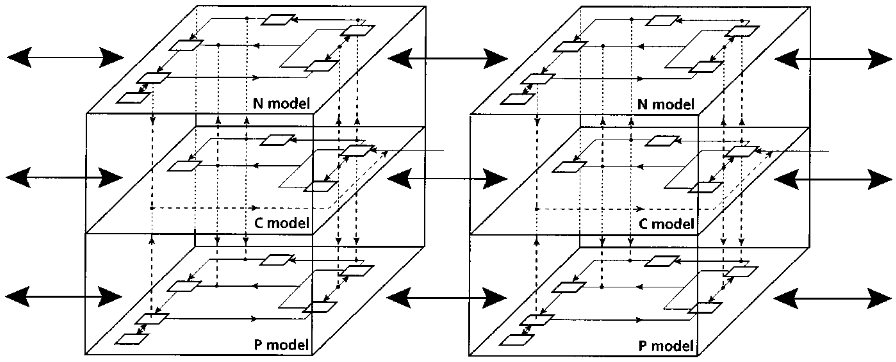


Figure 1. A conceptual diagram of a site-model consisting of two unit-models. Each unit-model consists of a nitrogen sub-model, a carbon sub-model and a phosphorus sub-model (see also Van der Peijl & Verhoeven 1999). Within these sub-models there is internal cycling. Landscape geochemical flows are shown between the unit-models.

sub-model. The state variables are the amounts of C, N and P in various plants pools, soil pools and herbivores, and are expressed as grams of C, N or P per m^2 surface area.

The plant-related state variables are: carbon, nitrogen and phosphorus in shoots and in roots; nitrogen and phosphorus retained in the plant after retranslocation of nutrients from dying plant material; and C, N and P in dead shoots and dead roots. Soil-related state variables are: carbon, nitrogen and phosphorus in soil organic matter; plant available nitrogen (nitrate and ammonium) and phosphorus; and phosphorus unavailable to plants. For state variables related to soil, only the active top layer, as indicated by the rooting depth of the vegetation, is included in the model. This rooting depth will differ for different sites. State variables related to herbivores are carbon, nitrogen and phosphorus in herbivores.

Within each sub-model the state variables are connected through flows of carbon, nitrogen or phosphorus. These flows (or processes) are expressed as grams of C, N or P per m^2 per week. They comprise processes associated with assimilation, respiration, translocation of nutrients, retranslocation and remobilisation of nutrients, death, fragmentation of litter, microbial processes in the soil, adsorption and release of P, grazing by herbivores, flooding of the site, mowing, burning and other management measures. There are 75 flows, of which 31 are inputs and outputs.

Wetlands are characterised by a fluctuating water table which gives rise to fluctuations in soil oxygen content and redox status, which in turn influence many soil and plant processes. The model deals with this by defining a con-

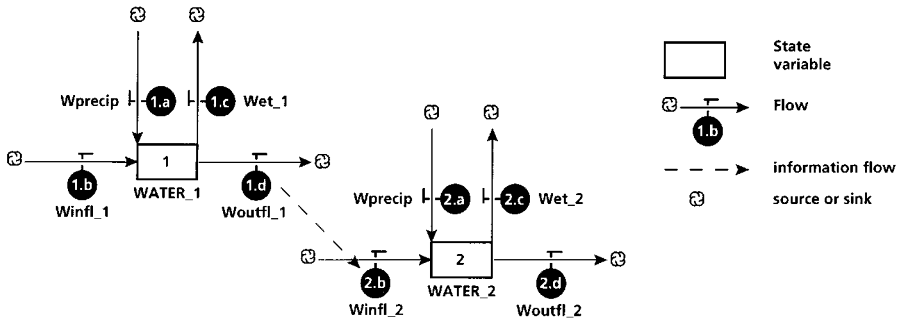


Figure 2. A conceptual diagram of the hydrological sub-models for two landscape units, representing a slope area (unit 1) with runoff from agricultural uplands and a floodplain (unit 2) between this slope and a river channel. The state variables are the amounts of water in the units, expressed as L/m^2. Water inflows into the units are the inflow from uphill and precipitation. The outflows are an outflow downhill and evapotranspiration. For an explanation of the state variables and flows, see Table 1.

trolling factor called 'mode', which integrates information on the water table, soil oxygen content and redox potential.

Values for the parameters in the model were obtained from data collected in 3 years of fieldwork, from literature and from estimates. Some values were adjusted during a calibration of the model. A sensitivity analysis was also performed (Van der Peijl & Verhoeven 1999).

2.2 *Connecting the units – a hydrological sub-model*

2.2.1 *Water*

To connect the units, we added a simple hydrological sub-model to the model. A conceptual diagram is shown in Figure 2. The equations for a site consisting of two units are given in the appendix. Names of parameters and variables are explained in Table 1. Inflows to the unit are water inflow and precipitation; outflows are evapotranspiration and water outflow (Equation 1 in the appendix).

The water budget works with a table input into the first (top) unit (1.b), which was derived from a larger hydrological model, made for the site (Papatolios et al. 1997). Precipitation (1.a) is known from meteorological data. Evapotranspiration (1.c) was calculated from potential evapotranspiration using the relation described in Koerselman (1989). The long term potential transpiration data was fitted to a sine curve (Equation 1.c.1). If the pF of the soil is above 4.2 there is no evapotranspiration. pF is an exponential function (Equation 1.c.2) of the fraction of the soil volume that is filled with water. Equations (1.c.3) and (1.c.4) were derived by assuming that the point

Table 1. State variables, flows and parameters newly defined or used in the hydrological sub-model. Hydrological parameters were measured by Papatolios et al. (1997). For other variables and parameters see Van der Peijl and Verhoeven (1999).

State variables	Description	No of eq. in Appendix	units	KM slope	KM floodplain
NNH4	Nitrogen as NH4 in the soil		gN/m^2		
NNO3	Nitrogen as NO3 in the interstitial water		gN/m^2		
PAVAIL	Phosphorus in the soil, directly available for plant uptake		gP/m^2		
WATER	The amount of water in the soil from 0 cm – depth	(1), (2)	$liter/m^2$		
Flows	**Description**	**No of eq. in Appendix**	**units**	**KM slope**	**KM floodplain**
NNH4_infl	Inflow of NNH4 into the unit from upslope (could be from a previous unit)	(7)	$gN/m^2/week$		
NNH4_outfl	Outflow of NNH4 downslope, to a next unit or to the river	(4)	$gN/m^2/week$		
NNO3_infl	Inflow of NNO3 into the unit from upslope (could be from a previous unit)	(8)	$gN/m^2/week$		
NNO3_outfl	Outflow of NNO3 downslope, to a next unit or to the river	(5)	$gN/m^2/week$		
PAVAIL_infl	Inflow of PAVAIL into the unit from upslope (could be from a previous unit)	(9)	$gP/m^2/week$		
PAVAIL_outfl	Outflow of PAVAIL downslope, to a next unit or to the river	(6)	$gP/m^2/week$		
Wet	Evapotranspiration	(1.c), (2.c)	$liter/m^2/week$		
Winfl	Water inflow from upslope (could be a previous unit)	(1.b), (2.b)	$liter/m^2/week$		
Woutfl	Water outflow downslope, to a next unit or to the river	(1.d), (2.d)	$liter/m^2/week$		
Wprecip	Precipitation	(1.a), (2.a)	$liter/m^2/week$		

Table 1. Continued.

Parameters	Description	No of eq. in Appendix	units	KM slope	KM floodplain
apf	Factor in the pF-curve	(1.c.3)	—	—	—
area	Area of the unit	constant	m^2	46800	10400
bpf	Factor in the pF-curve	(1.c.4)	—	—	—
cpf	Factor in the pF-curve	constant	—	49.8	49.8
depth	Soil depth in the model; rooting depth of the vegetation	constant	m	0.2	0.2
frin	Fraction of the output of the previous unit that goes into the next unit	constant	$week^{-1}$	10.01	
froff	Fraction of water on top of the soil that flow off the unit per week	constant	$week^{-1}$	10.95	
frout	Fraction of soil water that flow out of the unit per week	constant	$week^{-1}$	0.2	0.95
liters_out	Liters of water that flow out of the unit	(1.d.3)	liter/week	—	—
mode	Factor between 0 and 1 that describes the wetness/redox/ox% of the soil	(3)	—	—	—
NNO3_g_out	Grams of NNO3 flowing out of the unit	(5.a)	gN/week	—	—
NNH4_g_out	Grams of NNH4 flowing out of the unit	(4.a)	gN/week	—	—
PAVAIL_g_out	Grams of PAVAIL flowing out of the unit	(6.a)	gP/week	—	—
PF	^{10}log of the soil water pressure	(1.c.2)	—	—	—
Porosity	Porosity of the soil	constant	—	0.8	0.7
Pt	Potential evapotranspiration	(1.c.1)	liter/m^2/week	—	—

Table 1. Continued.

Parameters	Description	No of eq. in Appendix	units	KM slope	KM floodplain
Soilw_free	Soil water minus the soil water at field capacity	(1.d.2)	liter/m^2	—	—
Surfw	Surface water (water on top of the soil surface)	(1.d.1)	liter/m^2	—	—
Vegfact	Vegetation factor in evapotranspiration	constant	—	0.73	0.73
Vol_frac	Volume fraction of liquid	(1.c.5)	–		
Volume	Total volume of the soil (particles plus pores)	(1.c.6)	liter/m^2	200	200
Water_from_pu	Water inflow from upslope (could be a previous unit)		liter/week	—	—
Weeknr	Week number, the first week in a year is 1, the last is 52	—	weeks	—	—
Wfp	Water filled porosity	(3.a)	—	—	—
Wfp_fc	Water filled porosity at field capacity	constant	—	0.58	0.58

of inflexion of the pF curve is field capacity, and by assuming that pF is zero at wfp (water filled porosity) = porosity. In that way only 'cpf' in Equation 1.c.2 remains as a constant that has no physical meaning and needs to be estimated.

The outflow of water (1.d) is modelled as a constant fraction of the amount of soil water present in the site plus a constant fraction of the amount of water, if any, above the soil surface of the unit. Thus, at times of high rainfall, the outflow will be larger than at times of low rainfall. A certain fraction of the outflow enters the next unit (2.b), the rest leaves the system through ditches or as a deeper groundwater flow that does not enter another unit.

Values of parameters in the hydrological sub-model were derived from several years of hydrological fieldwork and from a much more complex hydrological model of the site, which was made independently (Papatolios et al. 1997).

2.2.2 *Mode*

The factor 'mode' is the most important factor controlling most process rates in the model. In the previous version of the model (Van der Peijl & Verhoeven 1999), 'mode', hereafter called 'mode_fdata', was derived from field data of soil oxygen content, redox potential and water table. For most sites this kind of data would probably not be available. However, with a working hydrological sub-model 'mode' can be derived from the water filled porosity (wfp, Equation 3.a). The redefined mode, 'mode_hyd' (Equation 3) is defined as the ratio of the fraction of pores that is not filled with water (1-wfp) to the fraction of pores that is not filled with water at field capacity (1-wfp_fc). Thus, mode is 1 when the water filled porosity equals the water filled porosity at field capacity, i.e., when the site is aerobic. Mode is 0 when the water filled porosity equals 1, i.e., the site is water-saturated and therefore anaerobic. The model was adjusted from calculating mode from field data to calculating it from the hydrological sub-model without altering overall model results. It made the model easier to apply to other sites.

2.2.3 *Nutrients*

The hydrological flows contain dissolved nutrients that flow into and out of the units with the water. Evapotranspiration and precipitation, however, are assumed not to contain any nutrients. Atmospheric deposition is modelled independently of precipitation. The amount of nutrients in the inflowing water is simply equal to the amount of water multiplied with the nutrient concentration of that water (Equations 7, 8 and 9). The amount of nutrients leaving the site is calculated in a slightly different way, as not all nutrients are equally mobile. Nitrate is highly mobile and therefore the amount of nitrate-N is simply the amount of outflowing water multiplied with the nitrate concentration (5). Ammonium is less mobile, therefore it is assumed that only a fraction (estimated and calibrated to be 20%) of the ammonium in the soil water flows out with the soil water (4). The rest remains in the unit. Phosphate is even less mobile and therefore the fraction that flows out is even smaller (estimated and calibrated to be 2%) (Equation 6). Furthermore it is assumed that surface runoff does not export any soil phosphate or ammonium.

2.3 *The application of a two unit model at Kismeldon Meadows*

A site-model consisting of two connected unit-models was developed for the same site that was described in Van der Peijl and Verhoeven (1999). This site, Kismeldon Meadows, Devon, south western England, consists of a slope unit and a floodplain unit. The hydrological input to the slope is groundwater discharge from agricultural uplands. This flow is not large as the soil is very impermeable ($< 10^{-3}$ m/day).

Because of changes to the river downstream, the floodplain does not usually flood any longer. Hydrological inputs to the floodplain are therefore mainly precipitation and runoff water from the slope. However, only a small fraction (estimated to be 1%) of the water that flows out of the slope unit enters the floodplain unit. The rest leaves the site through the ditches.

Table 2 shows the parameter values and initial values for the state variables that were used to run the model for the slope and floodplain. All values not in this table were identical for the slope and floodplain and can be found in Table 1.

2.4 *Simulation of restoration of the site*

The present system of ditches catching most of the water and nutrient output from the slope unit and thereby isolating the floodplain from its natural source at Kismeldon Meadows is clearly unnatural. Therefore a computer simulation experiment was performed to evaluate the more natural situation by “removing” the system of ditches from the area, allowing the water and nutrients from the slope to freely enter the floodplain. This increased the inflow of water into the floodplain by a factor of 100.

Table 2. Parameter values for the slope and floodplain of Kismeldon Meadows. Hydrological parameters were measured by Papatolios et al. (1997). For the sources of other parameters see Van der Peijl and Verhoeven (1999).

Parameter	Description	Units	Slope unit = 1	Floodplain unit = 2
area	Area of the unit	m^2	46800	10400
bulkdens	bulkdensity of the soil	g/cm^3	0.47	0.77
burnfract	fraction of the dead shoots that are being burned	—	0.8	0
cn_mo_0	C/N ratio of the decomposers in anaerobic circumstances	gC/gN	4.5	17
cn_mo_1	C/N ratio of the decomposers in aerobic circumstances	gC/gN	3.5	6.25
cp_mo_0	C/P ratio of the decomposers in anaerobic circumstances	gC/gP	110	110
cp_mo_1	C/P ratio of the decomposers in aerobic circumstances	gC/gP	80	60
depth	soil depth in the model; rooting depth of the vegetation	m	0.2	0.2
frin	Fraction of the output of this unit that goes into the next unit	$week^{-1}$	0.01	1
froff	Fraction of water on top of the soil that flows off the unit per week	$week^{-1}$	1	0.95
frout	Fraction of soil water that flows out of the unit per week	$week^{-1}$	0.2	0.95
h_0	efficiency of decomposers in anaerobic circumstances	—	0.1	0.1
h_1	efficiency of decomposers in aerobic circumstances	—	0.5	0.5
harv_level	amount of herbivores that is left on the site after harvesting	gC/m^2		
harv_week	time when part of the herbivores is ‘harvested’ by the farmer	weeks	40	40
km_ads	P concentration at which half of the maximum adsorption capacity of the soil is used	mgP/liter	12.47	6.09
num_herb_ha	grazing density (number of herbivores per hectare)	ha^{-1}	0.3	0.3
pads_maxdw	adsorption capacity of the soil on a dry weight basis	$\mu gP/g$	1299	1172
porosity	porosity of the soil	cm^3/cm^3	0.8	0.7
vegetation_type	code for vegetation type	—	1	2

Table 2. Continued.

Parameter	Description	Units	Slope vegtype = 1	Floodplain vegtype =2
k_dr_0	relative carbon decomposition rate in anaerobic circumstances	$week^{-1}$	0.000077	0.000385
k_dr_1	relative carbon decomposition rate in aerobic circumstances	$week^{-1}$	0.00077	0.00385
nconc_plws_opt	optimal concentration of N in the plant, disregarding stored N	gN/g	0.03	0.03
nretransfr	fraction of nitrogen in the plant that is retranslocated from dying tissue	—	0.4	0.2
pconc_plws_opt	optimal concentration of P in the plant, disregarding stored P	gP/g	0.0015	0.002
pretransfr	fraction of P in the plant that is retranslocated from dying tissue	—	0.77	0.2
rdr_ro_max	relative death rate of below ground plant biomass	$week^{-1}$	0.01	0.07
rdr_sh_max	relative death rate of above ground plant biomass	$week^{-1}$	0.04	0.1
rfr_rod_max	relative fragmentation rate of dead roots	—	0.00584	0.389
rfr_shd_max	relative fragmentation rate of dead shoots	0.00193	0.0193	
rgr_max	maximum relative growth rate of plants (gross assimilation)	$week^{-1}$	1.38	4.46
rrr_ro_max	relative respiration rate of plant roots	$week^{-1}$	0.01	0.07
rrr_sh_max	relative respiration rate of plant shoots	$week^{-1}$	0.482	0.482
sh_max	maximum aboveground biomass	gC/m^2	300	1000

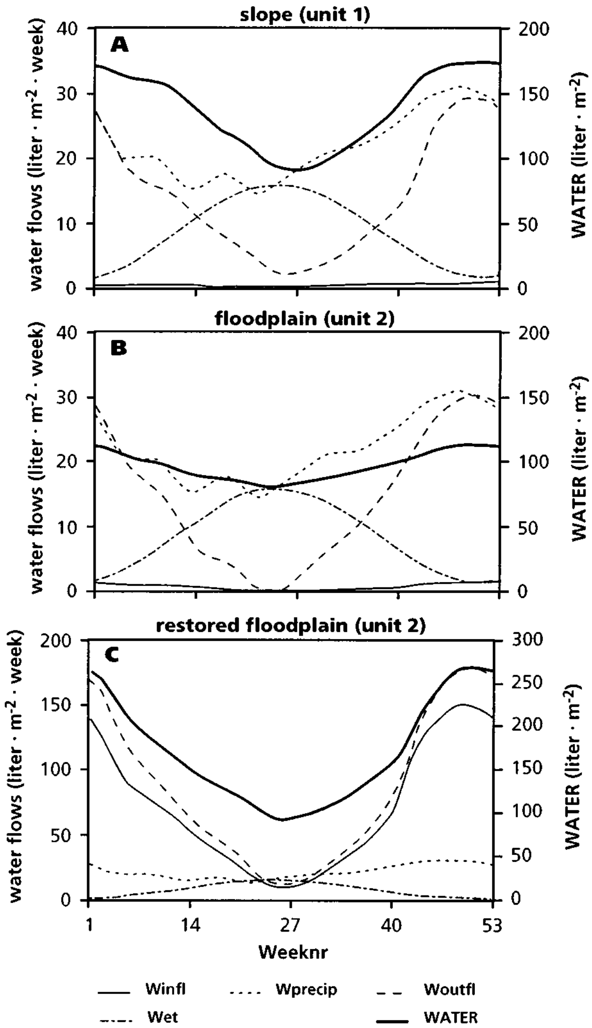


Figure 3. Water budgets for the slope (A), floodplain (B) and restored floodplain (C) units. The water inflows and outflows are shown in the left y-axis. The right y-axis shows the amount of water in the unit. Names of flows and state variables are explained in Table 1. Their equations are listed in the Appendix.

3. Results

3.1 *The application of a two unit model at Kismeldon Meadows*

Water budgets for the top 20 cm of the slope and floodplain, calculated by the hydrological sub-model, are shown in Figures 3(A and B). It can be seen that the water inputs to slope and floodplain are nearly the same, but because of

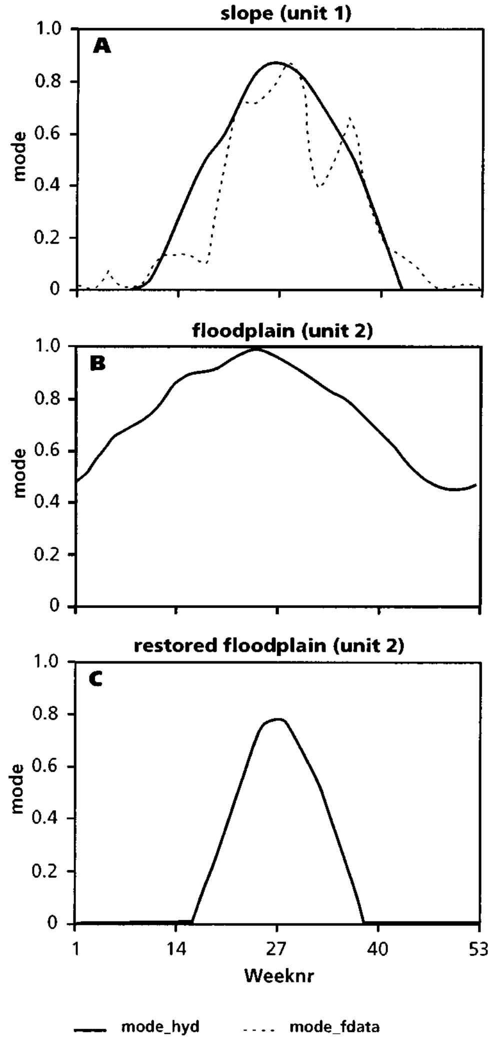


Figure 4. (A) Mode for the slope unit at Kismeldon Meadows, calculated in the hydrological sub-model (based on long-term meteorological data) ('mode-hyd') as well as based on 2 years of field measurements of oxygen content of the soil, redox potential of the soil and water. (B) Mode for the floodplain unit, based on the hydrological sub-model. (C) Mode for the restored floodplain unit.

the higher permeability (i.e., better drainage) of the soil, the floodplain unit is a lot dryer than the slope unit.

Figure 4(A) shows the 'mode-hyd' for the slope unit at Kismeldon Meadows, calculated in the hydrological sub-model based on long term meteorological data, as well as 'mode-fdata' based on 2 years of field meas-

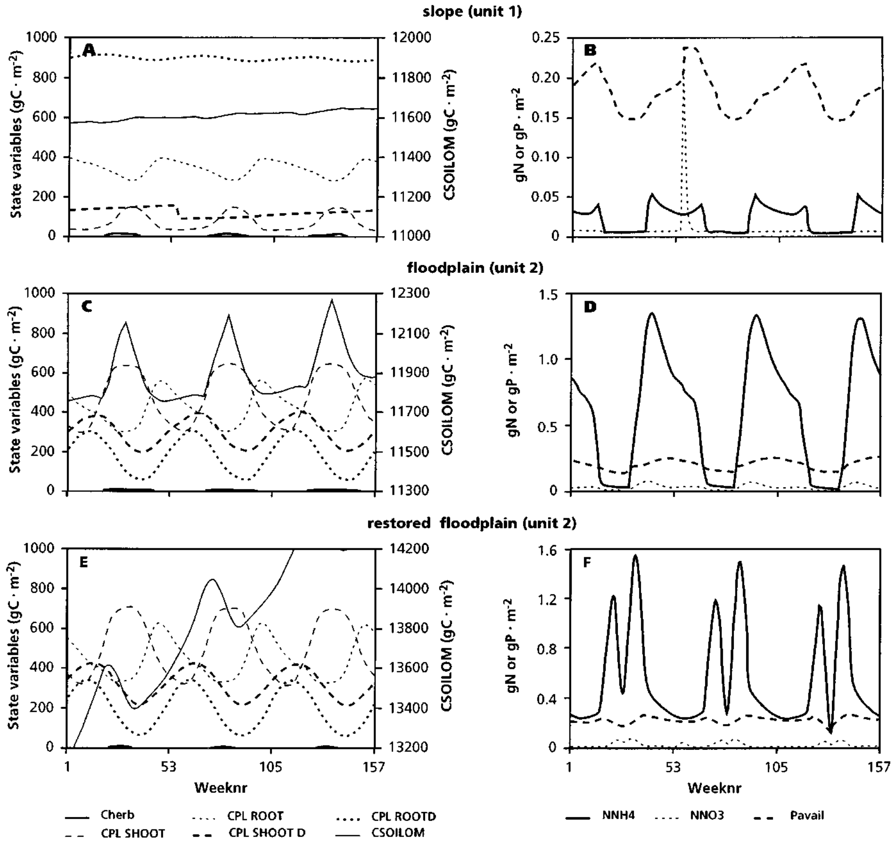


Figure 5. Dynamics of the state variables from the carbon sub-model (A, C and E) and plant available nutrients (B, D and F) in a 3-year simulation for the slope unit, the floodplain unit, and the restored floodplain unit, respectively.

urements of soil oxygen content, redox potential and water table (see Van der Peijl & Verhoeven 1999). The two methods give similar results but the mode based on the hydrological sub-model is smoother because it is based on long-term averages. Figure 4(B) shows mode for the floodplain unit, calculated from the hydrological sub-model. The unit is relatively dry (indicated by values of mode near to 1.0) for a prolonged period of the year, with a wetter period (indicated by lower values of mode) at the end of autumn.

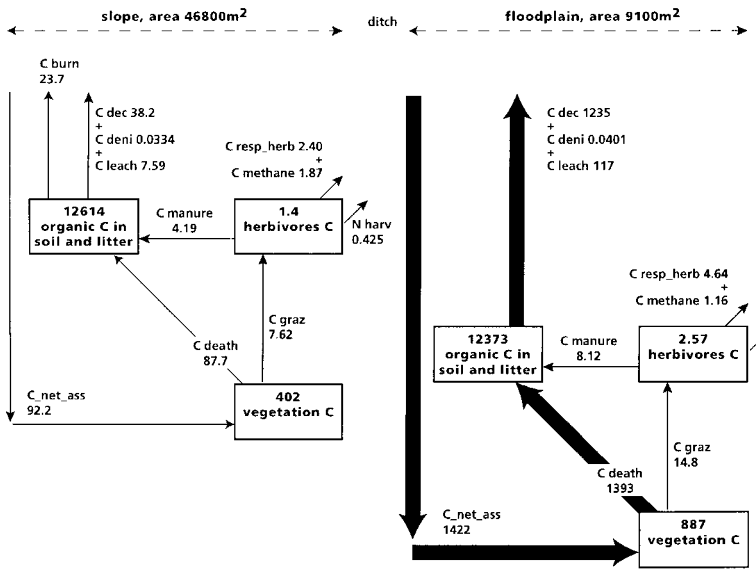
Figure 5(A) shows carbon in herbivores, living and dead plant roots and shoots, and soil organic matter and Figure 5(B) soil nutrients through time for the slope unit. Figures 5(C–D) show the same for the floodplain unit. Both slope and floodplain are quite stable as in the long run most state variables are constant, but with seasonal fluctuations. Soil organic matter, however, shows a gradual increase as in many natural systems (Odum 1969). The dip in standing dead plant material (Figure 5(A)) in the second year is caused by burning, which is part of the traditional management of the site. Burning also caused the peaks in soil nitrate and available P at that time and place (Figure 5(B)). The floodplain has higher plant biomass, soil organic matter and soil nutrient contents and also accumulates soil organic matter at a higher rate than the slope.

Figures 6(A–C) show 3-year averages of the state variables (g/m^2) and of the annual flows of carbon, nitrogen and phosphorus ($g/m^2/year$) respectively. The width of the arrows is proportional to the size of the flows. Nutrients cycling within the units are far greater than the amounts entering and leaving the units, and all flows are much higher in the floodplain than in the slope area. The total inflows, outflows, total amounts of nutrients present in each unit, and the amounts of nutrients that are cycling within the unit are also given in this table. The table also indicates whether an inflow or outflow is a landscape geochemical flow (LGF) or an extra landscape flow (ELF) in Kozlovskiy's classification.

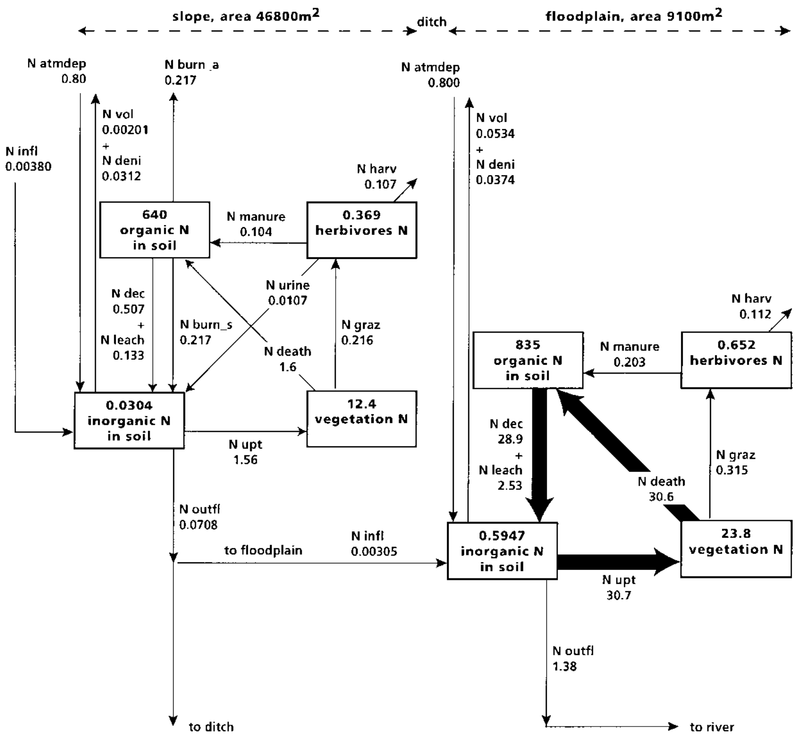
In the slope unit 0.13% of the N and 0.14% of the P in the system is part of the main migrational cycle (MMC). Most of the nitrogen is inactive in the organic matter. The main P pools are organic matter and inorganic adsorbed P. As the floodplain is more nutrient-rich than the slope, all processes are more rapid (a higher turnover rate) and therefore a higher proportion of the N and P (though still not very high), are cycling within the system (3.6% and 1.0%, respectively).

3.2 *Simulation of restoration of the site*

Connecting the slope and the floodplain completely changed the wetness of the floodplain unit and also increased the nutrient inflows. The water budget of the floodplain in this experiment is shown in Figure 3(C). Compared with Figure 3(B), the floodplain now has a much higher water inflow, and has become a lot wetter than it was before removal of the ditch. This is also clear from Figure 4(C), which shows mode, the factor that indicates how wet the soil is. The amount of inflowing nutrients to the floodplain is also increased with the higher water input. Figures 5(E and F) show the behaviour of the state variables in the carbon sub-model and the amounts of plant available nutrients with time. Compared to Figures 5(C and D), all state variables are a bit higher because of the higher nutrient inputs, and organic matter is accumulating more rapidly than before. Figure 7 shows 3-year averages of the state variables (g/m^2) and of the annual flows of carbon (A), nitrogen (B) and phosphorus (C) ($g/m^2/year$) for the floodplain in the new situation. The situation without restoration can be seen in Figures 6(A–C). Restoration

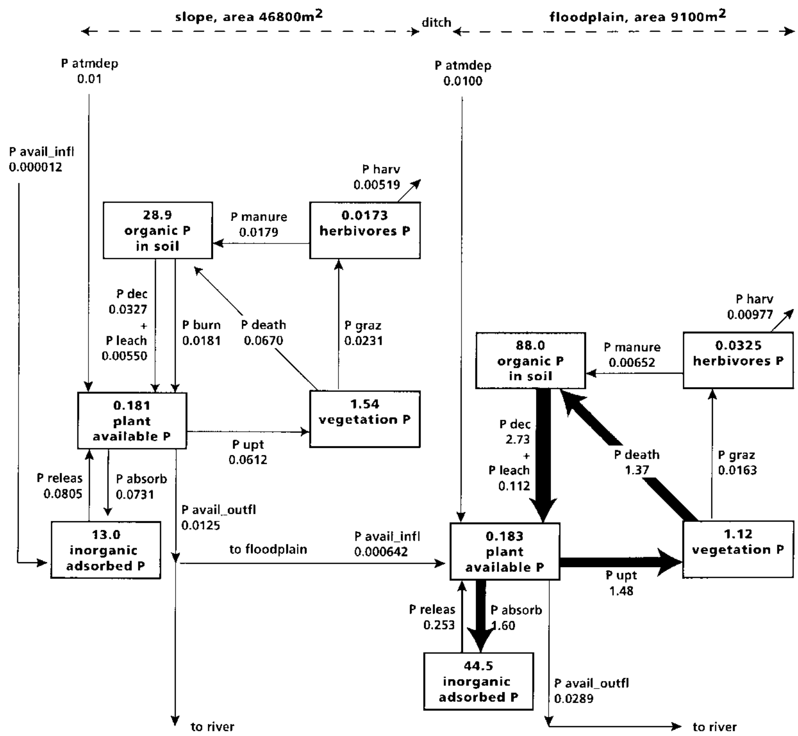


(A)



(B)

Figure 6. Carbon (A), nitrogen (B) and phosphorus (C) cycling (MMC) and inflows and outflows (LGF's and ELF's) on a yearly basis for the slope and the floodplain. The arrows that indicate the carbon and nutrient flows are proportional to the size of the flows.



(C)

Figure 6. Continued.

of the site causes more carbon accumulation in soil organic matter through simultaneous higher annual plant production (resulting in higher amounts of plant parts dying), and lower decomposition.

4. Discussion

4.1 *The water purification function of the wetland*

Interest in the functioning of a wetland as a net source or sink of nutrients often stems from a possible water purification function of the wetland (Kadlec & Knight 1996). The N concentration in water flowing out of the slope is on average substantially lower than that of the shallow groundwater flow from the agricultural upland, which is 0.319 mgN/litre. The N concentration of the outflowing water is approximately 0.06 mgN/litre in most of the year, with little peaks of 0.12 mgN/litre in spring and autumn. Only just after the burning of the standing dead material, there is a short period when, because of all the nitrogen that suddenly becomes available, the N concentration of

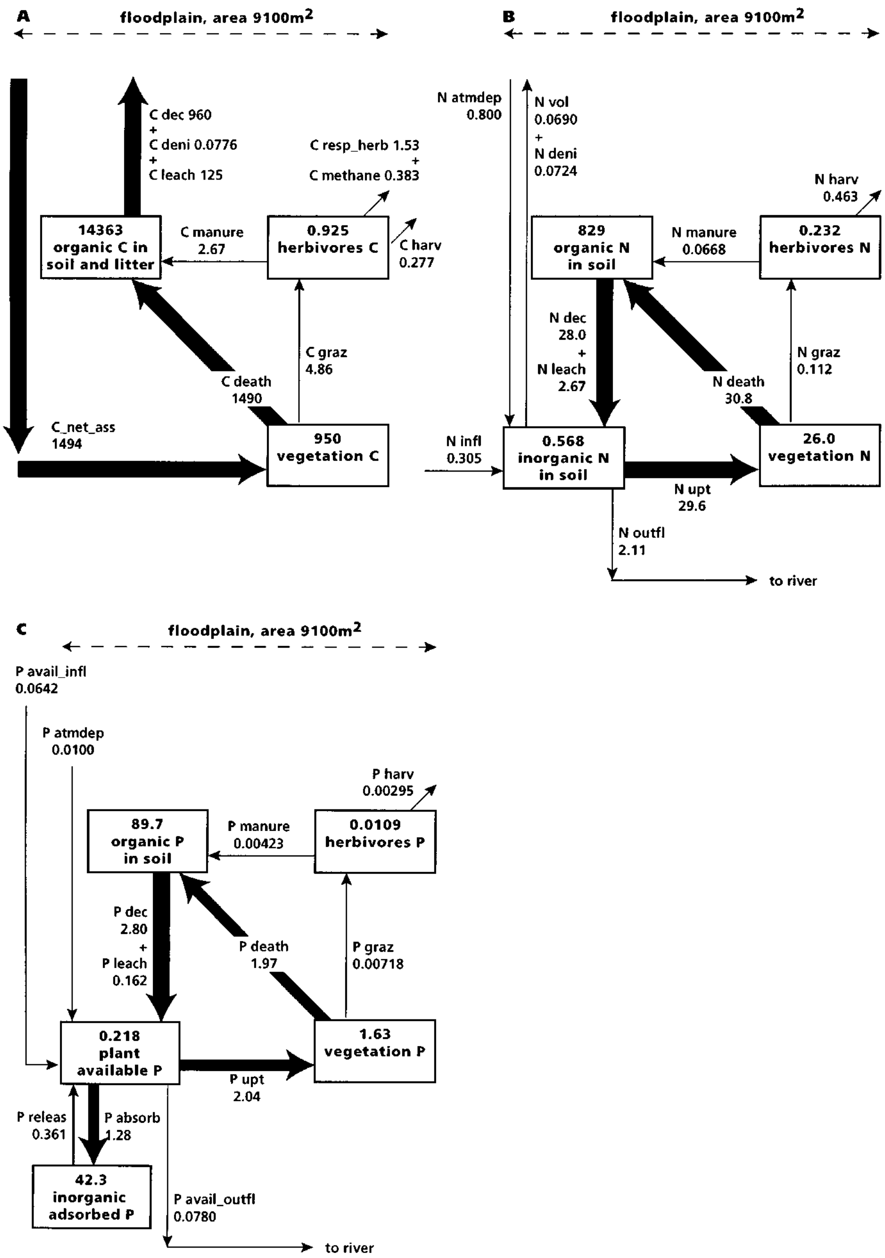


Figure 7. Carbon (A), nitrogen (B) and phosphorus (C) cycling and inflows and outflows (LGF's and ELF's) on a yearly basis for the floodplain after connecting it to the slope. The arrows that indicate the carbon and nutrient flows are proportional to the size of the flows. Compare with Figure 6.

the outflowing water is as high as 3.8 mgN/litre, which is much higher than that of the inflowing water. The P concentration of the shallow groundwater flow into the slope is 0.001 mgP/litre. The P concentration in the outflowing water fluctuates between 0.03 mgP/litre and 0.01 and is at all times higher than that of the inflowing water.

An estimated 1% of the water flowing out of the slope enters the floodplain. The concentrations of N and P in the water flowing into the floodplain are equal to those of the water flowing out of the slope. The N concentration of the inflowing water is between 0.06 and 0.12 mgN/litre, with very short peaks of 3.8 mgN/litre as was mentioned above. The N concentration in the water flowing out of the floodplain into the river shows a similar seasonal pattern as that in the inflowing water, but is always higher than that, namely between 0.15 and 3 mgP/litre. The peaks in the concentration caused by burning of the slope, do not occur in the water that flows out of the floodplain. The P concentration in water flowing out of the floodplain into the river is between 0.03 and 0.045 mgP/litre and is always higher than that of water flowing into the floodplain.

4.1.1 *The unit as a net nutrient source or sink*

The fact that nutrient outflows do not equal inflows does not necessarily mean that the wetland acts as a net sink or source of nutrients to its environment. Nitrogen also has a gaseous phase and can be denitrified, volatilise or be subject to fixation. Further, nutrients may be diluted or concentrated as a result of precipitation and evapotranspiration.

According to the model, at present the slope acts as a net sink of nitrogen and a source of phosphorus to the environment. The slope unit shows a net accumulation of 0.375 gN/m^2/year, which is substantial compared to the amount that is cycling within the system (0.857 gN/m^2/year). This nitrogen is stored in the soil organic matter pool, which does increase (Figure 5(A)). The concentration of nitrogen in the soil organic matter remains practically constant (a reduction of less than 1% of the initial concentration occurred in an 8-year run).

The slope unit shows a net loss of 0.00767 gP/m^2/year. At the same time the system is accumulating soil organic matter and the P concentration in this soil organic matter is virtually constant (a reduction of less than 1% of the initial concentration occurred in an 8-year run). Both the phosphorus that is lost in hydrological outflows and through grazing, and the phosphorus that accumulates in soil organic matter stem from the pool of adsorbed P in the soil. The decrease of this pool of adsorbed P is only 0.045% per year, so this is not likely to change the functioning of the system, even on the longer term.

Net accumulation of soil organic matter is a common phenomenon in undisturbed ecosystems (Odum 1969). Wetlands have been found to either be net sinks or net sources for nitrogen and phosphorus (Mitsch & Gosselink 1986). Wetlands being a source for one element while being a sink for the other element is not unusual. It could be hypothesised that systems are likely to be a sink for the element that is the most limiting for plant growth and that they may be a source for other nutrients at the same time.

Unlike the slope, the floodplain is losing nitrogen. The floodplain is accumulating soil organic matter (Figure 5(A)), but the nitrogen concentration in the soil organic matter is decreasing very slowly (about 0.5% of the initial value per year). Net nitrogen loss from the floodplain is 0.775 gN/m^2/year. At the floodplain the P concentration in soil organic matter is decreasing (about 2.5% of the initial concentration per year), while the amount of soil organic matter is increasing. Part of the P that is released, becomes part of the pool of adsorbed P and part flows out of the floodplain into the river. The floodplain is net losing phosphorus at a rate of 0.028 gP/m^2/year.

The net loss of N and P from the floodplain could be explained by its history. Former riverine sedimentation caused the floodplain to be nutrient-rich, certainly compared to the slope unit. In this situation presumably N and P have accumulated. Because of human impacts downstream, the flooding regime has changed so much that the floodplain does not regularly flood any more. Thus the floodplain has been cut off from its former main nutrient source, and the nutrient pools in the floodplain are no longer in balance with their inputs and outputs. The result is a net loss of nutrients.

It can be concluded that the units examined (slope and floodplain), indeed, acted as a sink or source for a nutrient when the nutrient concentration of the water flowing through the unit decreased or increased, respectively. These changes in concentrations were not due to hydrological processes, such as dilution or evapotranspiration.

4.2 *The importance of nutrient inputs relative to nutrient cycling*

In the slope as well as the floodplain, most of the nutrients are in soil pools that are not very active, i.e., have very long turn-over times. Nitrogen is mainly stored in soil organic matter (98% of total N at the slope and 97% at the floodplain) and phosphorus is mainly present in soil organic matter (65% of total P at the slope and 66% at the floodplain) and as adsorbed phosphorus (29% of total P at the slope and 33% at the floodplain) (Figures 6(B and C)). That most of the N and P are in pools with low turn-over rates is common to systems that are not in an initial phase. Undisturbed ecosystems are thought to change through time from ‘open’ systems with high flow-through compared to storage, to ‘closed’ systems with large stores compared to inputs and outputs (Howard-Williams 1985; Odum 1971).

Compared to the total amounts of nutrients in the system, all flows (inflows, outflows and the amounts that are cycling) would seem insignificant (all are less than 0.27). However, flows must be considered in relation to the amount of ‘active’ nutrients, rather than total stored nutrients. Flows (g/m^2/year) could expressed as fractions of the (average) size of the total pool of available nutrients in the soil (g/m^2). However, because available nutrients turn over rapidly (e.g., 0.02 year for available soil nitrogen in the slope unit), this would substantially underestimate the amount of active nutrients in a whole year.

At the nutrient-poor slope unit, by far the most important nitrogen (N) and phosphorus (P) inputs are from atmospheric deposition, an Extra Landscape Flow (ELF, Kozlovskyi 1972) amounting to 99% of total inputs. Hence, the inputs through water inflows (Landscape Geochemical Flow, LGF) are relatively small. Nitrogen cycling (Main Migrational Cycle, MMC, 0.857 gN/m^2/year) and nitrogen input into the system (0.804 gN/m^2/year) are about equally important as supplies of inorganic nitrogen that can annually be taken up by the vegetation (uptake = 1.56 gN/m^2/year, Figure 6(B)).

As the amount of nitrogen input is almost equal to the amount of nitrogen cycling and the system is close to a stable state, the annual input of nitrogen is probably very important, if not essential, in maintaining the system. For the P cycle the P inputs (ELF + LGF) are less important, compared to the amount cycling (MMC).

The most important nutrient inputs to the more nutrient-rich floodplain are also from atmospheric deposition (ELF), but compared to the amounts that are cycling within the system (MMC), these are minor ($<$3% of N and $<$1% of P). At this site nutrient turnover rates are much higher and most nutrient cycling is from internal cycling. Nutrient inputs from the slope were very low compared to inputs from atmospheric deposition.

Seventeen percent of the nitrogen that leaves the slope unit is in the water outflow (LGF); the rest leaves the unit in gaseous forms (ELF’s) through denitrification (7%), volatilisation ($<$1%) and burning (51%), or through grazing (25%). Phosphorus that leaves the unit is in the water outflow to the river (LGF, 71%) or in herbivores (ELF, 29%) as no gaseous forms of P occur naturally (Johnston 1994).

Hence, the relative importance of ELF’s and LGF’s differ between nitrogen and phosphorus and between nutrient-rich and nutrient-poor units. In the slope unit the main nitrogen and phosphorus inputs are from atmospheric deposition, an ELF. In the output from the nutrient-poor slope unit, most of the nitrogen is in ELF’s, but most of the phosphorus is in the LGF. As most of this LGF does not reach the floodplain, in the input into the floodplain unit, the ELF's are more important. In the outflows out of the nutrient-rich floodplain, the LGF's are always more important than the ELF's. In conclusion, (1) LGF's are more likely to be important compared to ELF's in the phosphorus cycle than in the nitrogen cycle and (2) the more nutrient-rich a place is, the more important LGF's become compared to ELF's.

4.3 *Simulation of restoration of the site*

Connecting the slope and floodplain by removing the ditch had several effects. Firstly, by higher water inflows the floodplain unit became much wetter. The wetness throughout the year became much more similar to that of the slope unit. This influenced many process rates. Secondly, grazing in the floodplain decreased, because it can only occur when the site is sufficiently dry. Thirdly, the higher water inflows brought more nutrients from the slope into the floodplain unit.

The wetter soil at the floodplain led to less decomposition. This also caused less nutrients to become available through mineralisation, which was, however, more than compensated for by the higher nutrient inputs from the slope area. The higher nutrient levels in the floodplain led to higher biomass production and this caused more new soil organic matter to be formed. Both effects together (more formation of organic matter and less decomposition) caused a faster accumulation of soil organic matter.

Connecting the slope to the floodplain increased the amount of nutrients in water flowing into the floodplain (LGF) relatively to the inputs by atmospheric deposition (ELF), especially for P. However, in the floodplain both nitrogen and phosphorus internal cycling remained far more important than the inputs.

An overall effect of connecting the slope and the floodplain has been examined by adding up the total annual loads of nutrients into the river. In the present situation (Figure 6(B)), the nitrogen input into the river from the slope is 99% of the total flow from the slope and equals 3.3 kg N/year. The input from the floodplain equals 12.6 kg N/year, which brings the total input to 15.9 kg N/year. The total annual P input equals (Figure 6(C)) 0.84 kg P/year. After connecting the slope and the floodplain, the total N input into the river is (Figure 7(B)) 19.2 kg N/year and the annual total P input is (Figure 7(C)) 0.71 kg P/year. Thus, the overall effect of connecting the slope and the floodplain is higher nitrogen inputs into the river, but lower phosphorus inputs.

The effect of the slope and floodplain together on especially the nitrogen input into the river is substantial, mainly because of their wetland character. If the slope and floodplain areas would be inert to nutrients, the input of N to the river would equal the flow from the agricultural uplands plus the atmospheric deposition on the area, i.e., 44.9 kg N/year. The wetlands remove a substantial part of this nitrogen. The input of P into the river would be somewhat lower without the wetlands, namely from the agricultural uplands plus atmospheric deposition 0.56 kg P/year.

4.4 *Conclusion*

Though the sizes of the LGF's and ELF's are relatively small compared to the amounts of nutrients cycling within the units, these flows are very important for maintaining the functioning of the system, especially in nutrient-poor units with a low productivity. The LGF's in the present situation were not very important due to the bypass of water through a ditch towards the river. Restoring the connection between slope and floodplain substantially increased the flows from the slope to the floodplain and changed the nutrient cycling in the floodplain. The increased nutrient input into the floodplain led to a higher biomass production, whereas the increased wetness of the floodplain caused slower decomposition. These two effects resulted in a faster soil organic matter accumulation.

To understand the functioning of a whole catchment it is necessary to examine the landscape geochemical flows and extra landscape flows and how much they contribute to nutrient cycling and the functioning of the system. The modelling approach described in this paper demonstrates the importance of these flows and their influence on the functioning of the catchment.

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Appendix

HYDROLOGY

Unite 1: a slope unit

$$WATER\_1(t) = WATER\_1(t-dt) + (Wprecip + Winfl\_1 - Wet\_1 - Woutfl\_1) * dt \tag{1}$$

$$Wprecip = graph(weeknr) \tag{1.a}$$

$$Winfl\_1 = water\_from\_pu/area\_1 \tag{1.b}$$

$$Wet\_1 = \begin{cases} vegfact\_1 * pt + 1.12 & pF\_1 \leq 4.2 \\ 0 & pF\_1 \geq 4.2 \end{cases} \tag{1.c}$$

$$pt = 10.14 + 9.79 * \sin(2 * \pi/52 * (weeknr + 39.9)) \tag{1.c.1}$$

$$pF\_1 = \begin{cases} 7 & vol\_frac\_1 \leq 0 \\ 7 + apf\_1 * vol\_frac\_1 + bpf\_1 * & \\ \quad vol\_frac\_1^2 - cpf\_1 * vol\_frac\_1^3 & 0 < vol\_frac\_1 < porosity\_1 \\ 0 & vol\_frac\_1 \geq porosity\_1 \end{cases} \tag{1.c.2}$$

$$apf\_1 = (1 - 3 * wfp\_fc\_1) * c\_1 * porosity\_1^2 - 7/porosity\_1 \tag{1.c.3}$$

$$bpf\_1 = 3 * wfp\_fc\_1 * porosity\_1 * cpf\_1 \tag{1.c.4}$$

$$vol\_frac\_1 = WATER\_1/volume\_1 \tag{1.c.5}$$

$$volume\_1 = depth\_1 * 1000 \tag{1.c.6}$$

$$Woutfl\_1 = frout\_1 * soilw\_free\_1 + froff\_1 * surfw\_1 \tag{1.d}$$

$$surfw\_1 = \begin{cases} 0 & vol\_frac\_1 \leq porosity\_1 \\ (vol\_frac\_1 - pososity\_1) * volume\_1 & vol\_frac\_1 > porosity\_1 \end{cases} \tag{1.d.1}$$

$$soilw\_free\_1 = \begin{cases} (1 - wfp\_fc\_1) * porosity\_1 * volume\_1 & vol\_frac\_1 > porosity\_1 \\ (vol\_frac\_1 - wfp\_fc\_1 * porosity\_1) * & \\ \quad volume\_1 & wfp\_fc\_1 * porosity\_1 < vol\_frac\_1 \leq porosity\_1 \\ 0 & vol\_frac\_1 \leq wfp\_fc\_1 * porosity\_1 \end{cases} \tag{1.d.2}$$

$$liters\_out\_1 = Woutfl\_1 * area\_1 \tag{1.d.3}$$

Unit 2: a floodplain unit

$$WATER\_2(t) = WATER\_2(t-dt) + (Wprecip + Winfl\_2 - WET\_2 - Woutfl\_2) * dt \tag{2}$$

Equation (2.a) is identical to Equation (1.a).

$$Winfl\_2 = frin\_2 * liters\_out\_1/area\_2 \tag{2.b}$$

Equations (2.c) and (2.d) are analogous to (1.c) and (1.d).

$$mode\_1 = \begin{cases} 0 & wfp\_1 \geq 1 \\ (1 - wfp\_1)/(1 - wfp\_fc) & wfp\_fc\_1 < wfp\_1 < 1 \\ 1 & wfp\_1 \leq wfp\_fc\_1 \end{cases} \tag{3}$$

$$wfp\_1 = vol\_frac\_1/porosity\_1 \tag{3.a}$$

NUTRIENT OUTFLOWS

$$NNH4\_outfl\_1 = 0.2 * NNH4\_1/(WATER\_1 - surfw\_1) * soilw\_out\_1 \tag{4}$$

$$NNH4\_g\_out\_1 = NNH4\_outfl\_1 * area\_1 \tag{4.a}$$

$$NNO3\_outfl\_1 = NNO3\_1/WATER\_1 * Woutfl\_1 \tag{5}$$

$$NNO3\_g\_out\_1 = NNO3\_outfl\_1 * area\_1 \tag{5.a}$$

$$PAVAIL\_outfl\_1 = 0.02 * PAVAIL\_1.(WATER\_1 - surfw\_1) * soilw\_out\_1 \tag{6}$$

$$PAVAIL\_g\_out\_1 = PAVAIL\_outfl\_1 * area\_1 \tag{6.a}$$

NURIENT INFLOWS

$$NNH4\_infl\_2 = frin\_2 * NNH4\_g\_out\_1/area\_2 \tag{7}$$

$$NNO3\_infl\_2 = frin\_2 * NNO3\_g\_out\_1/area\_2 \tag{8}$$

$$PAVAIL\_infl\_2 = frin\_2 * PAVAIL\_g\_out\_1/area\_2 \tag{9}$$

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