Lanscape control on diffuse pollution : a critical review on some investigations on phosphorus – retaining landscape features

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Landscape control on diffuse pollution: a critical review on some investigations on phosphorus – retaining landscape features

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Abstract

This text focuses on the identification, efficiencies, classification and management of landscape features having a potential buffer function regarding diffuse phosphorus, because of their specific structure (vegetation-soil) and of their location at the interface between sources (farm infrastructures, emitting fields…) and surface water bodies. These buffers are very diverse and correspond to natural landscape features (wetlands, riparian areas…) as well as manmade structures (constructed buffer strips or intermediate cases such as field margins, hedgerows). Their role and efficiency depends on the local factors controlling the retention processes (internal organisation and properties of the buffer), on the position within the watershed, and on the landscape context which reciprocally determines the overall buffer capacity of a watershed. On that basis, we recognize the diversity of the buffers in structure and functioning and thus in the way they attenuate the signal, their limitations (sustainability, side effects) and their hierarchic organisation at the watershed scale.

Key words

Phosphorus, diffuse pollution, buffer strips, landscape, wetlands agriculture

INTRODUCTION

Over the past 2 or 3 decades, the greatest achievement for eutrophication control, has been to obtain a drastic reduction of point sources and begin to implement measures aimed at controlling non-point sources, including agricultural diffuse sources. Diffuse phosphorus (P) has often been identified as a major candidate for pollution control because of the threat of continued P-loading further driving or maintaining eutrophication (Sharpley, 1995; Lake Champlain Management Conference, 1996; CIPEL, 1988…). In Europe, new expectations from aquatic ecosystems, especially lakes (water supply, European water framework directive), new pressures on the watershed combined with the initial effects of climatic change, reinforce the need of a new step in the control of non-point phosphorus. This often led lake managers, to ask scientists operational questions about diffuse agricultural sources of P. An initial set of questions is related to the contribution of P originating from agricultural lands to eutrophication. Another set of questions deals with the achievement of a reduction of P fluxes: which part of watershed P-inputs are controllable? Are the BMPs systems, designed all over the world, implementable in our specific rural context? Should we design a site-specific BMPs system? Can we rely on landscape elements which intercept and retain pollutant ("buffer zones") to reduce fluxes in the specific case of phosphorus.

Given these questions, we developed a set of studies whose general objective was the understanding of the diversity and variability of phosphorus diffuse transfer and transformation at the watershed scale. Our objectives were not to characterize processes and factors involved in P transfer (which are well documented, see e.g. Ryden et al 1973; Sharpley et al 1993; Heathwaite et al 2000, Michaud et al, 2005…), but to understand how landscape features and dynamics distort and organize these processes in space and time, and finally how these factors largely govern the pattern of the P export regime.

We considered mainly medium sized watersheds within a "heterogeneous landscape" which means, presenting a matrix of diverse agricultural fields mixed with patches of non-agricultural land coverage. Heterogeneous landscapes are quite common in Europe and are good models for understanding the importance of landscape structure and organisation, on pollutant fluxes.

In this paper we aim to focus on the buffers as a key aspect of field to watershed scale diffuse phosphorus control and management. Our objective is to review and discuss a series of studies dealing with the mechanisms and assessment of buffer effects at the local and landscape scale. The general questions which form the background to this work are: how do the activities on, and organization of, the landscape contribute to create diverse buffers and thus to attenuate P transfer and export? How can we maximize these effects? How can they be part of a mitigation options strategy?

We use both a theoretical approach, selected bibliography and specific results of our experiments and empirical studies in Lake Geneva (Lac Léman) areas and in Brittany (France), to: 1) conceptualize and categorize buffers effects; 2) classify landscape elements which have the potential to act as buffers; 3) analyse the diversity of conditions and functioning that attenuates P; 4) understand the role of the spatial position of the landscape elements, and of practices that take place within each type (human factors).

CONCEPTUAL FRAMEWORK

Rural landscape as a nutrients transfer system: sources and interfaces.

Transfer system

Rural landscapes are hierarchical mosaics consisting of agricultural fields, non-agricultural lands such as forests or wetlands, and farm infrastructures. All of these components are connected by linear structures such as roads, field margins and riparian strips, and arrayed in the hydrographic network. The landscape components are distributed in space according to natural landscape factors, mainly hydrological and morpho-pedological settings, and to anthropogenic processes, mainly agricultural practices reflecting farm objectives and constraints, and rural development.

The movement of P through the landscape to the outlet of the corresponding watershed is highly variable in space and time. It results in a chain of interacting and cascading processes including, emission from sources, hydraulic transport, storage in landscape sinks and export to receiving water bodies (Wang et al, 2004). The landscape components operating these transfer processes form the "transfer system".

The P transfer system is characterized by the nature and location of the sources (soil surface), the nature of the flows connecting these sources to the hydrographic network (mainly convergent or sheet surface flows, but also soil matrix flows, piped/ditched flows) and finally by the interaction of flows transporting P with certain types of landscape features. The transfer system regulates the P export regime at the outlet (quantity, quality and timing). This regime is more variable for "particulate-P" (P bounded to particles) than for "dissolved-P" (dissolved forms of P; dissolved- and particulate-P together form "total–P; for P speciation, see Haygarth and Sharpley, 2000)

P sources

In agricultural watersheds, farm fields (mainly tilled fields with some intensive pastures) and farm infrastructures usually represent the main sources of diffuse total-P for water bodies. The P inputs from farm fields are mainly stochastic (from infrequent and sometimes erosive storm events), but secondarily show an annual/seasonal pattern (associated with seasonal precipitation trends, fertilisation timing and biomass decomposition). Dissolved-P is more sensitive to seasonal dynamics (Jordan-Meille and Dorioz, 2004). Fluxes emitted by fields are at a maximum when high-P sources (which depend on practices) coincide with transport factors (erosion, occurrence of surface runoff, local hydrology…). Identifying these

"critical source areas" allows the selection of places to preferentially implement mitigation options. Wheel tracks or compacted soil surfaces, which often directly connect crop lands to stream networks, combine to create such high risk areas (Heathwaite et al., 2005).

Mitigation options at the field level are based upon two simple principles (1) control of fertilisation inputs (adjustment of quantity and timing of applications), and (2) development of practices which reduce surface runoff and erosion. The latter corresponds to measures that maintain a high soil infiltrability, avoiding inappropriate practices of soil tillage, crop harvesting or management of inter-crop.

Interfaces and buffers

Non-field farm landscape entities are very diverse and can be classified by their contribution to the transfer system in:

(i) "landscape interfaces", meaning all kinds of landscape structures or sets of structures, situated between phosphorus sources and the hydrographic network; when surface and/or subsurface runoff flows through them, these interfaces act either as sinks, (which attenuate P transfer to varying degrees and are called "buffer interfaces"), or as "connecting media", ensuring a hydraulic connection (fluxes flow through these structures with no major change);

(ii) neutral components, providing a flow of water, which dilutes the concentration of pollutants at the outlet of the watershed.

Landscape interfaces modulate the hydraulic connections within a watershed. The surface runoff enters and flows through the interfaces in a diffuse or concentrated way. Interfaces are very diverse in term of shape, size, and origin. They can be narrow strips, constituting just technical spaces maintained by farmers between their fields and other components (roads, ditches, streams, or other fields). They can be larger landscape elements, made up of fragments of semi-natural landscape (e.g. wetlands, hedgerows…) or vegetative structures constructed intentionally to be buffers.

Buffer and buffer capacity

Concept

The heterogeneity of the landscape has often been considered as a state favourable for trapping diffuse pollutants emitted by farm fields, leading to the concept of buffers and the definition of the "buffer capacity" of a watershed (Haycock *et al.*, 1997; Viaud *et al.*, 2004). The buffer capacity is usually attributed to a few landscape structures, called buffers, which respond to incoming water flows and associated nutrients or contaminants, by temporary and often selective, retention and transformation of some of these pollutants. Buffers play such a role because of their structure and location between water bodies and sources. Interactions between pollutants and these components of the landscape either limit the amount delivered to watercourses or alter the timing of the delivery. The latter effect can be beneficial if it prevents discharges during key sensitive periods of the receiving aquatic ecosystems.

The buffer capacity is universally measured as the ratio between pollutant emissions from the sources (fields) and the amount delivered to the water bodies, with the buffering effect being indicated by a lowering of the pollutant load or an attenuation of the temporal dynamics of the emission, beyond the buffer zone. This measure is applicable from the field to the watershed scale. For total-P, changes in bio-availability should also be taken into account.

Faced with the diversity of structures and processes involved in buffer effects, Viaud *et al.* (2004) proposed a synthetic approach. Inputs and outputs are treated as "signals" (flows and concentrations, or rates). Thus the metrics of the buffering effect is not restricted to mean values, but also include changes in frequency, variability, and range (fig 1a). Regarding total-P the buffer system receives an inflow of surface or subsurface runoff containing particulate- and/or dissolved-P (the "input signal") and releases an "output signal" of a similar nature to down-gradient surface waters. The output signal varies in many ways from the input, with a modified concentration, flux, variation, and/or frequency.

This approach leads Viaud *et al*. (2004) to differentiate several types of buffer according to the signal modulation induced. We will consider only 4 types (fig 1b): "barriers" which stop the propagation (no output signal), "attenuating filters" which decrease the mean level signal and can have a selective effect (e.g. dissolved/particulate), "selective barriers" which limit the maximum values of fluxes and "retardant filters" which introduce a lag in the transfer. Of course there are mainly of intermediate cases and some temporal variability. Whatever the type of buffer, biogeochemical transformations of P can occur.

Biogeochemical aspects, implications for buffer capacity

The basic processes involved in all buffering effects are well documented (e g. Dillhaha *et al*., 1997; Uusi-Kampa *et al*., 1997; Benoit *et al*., 2004). First of all buffers intercept runoff, retain and store water and/or sediment and consequently the pollutant loads associated. Once pollutants are retained, biogeochemical regulation and transformation may occur.

Particulate-P is easily retained in all kinds of places and structures where the sediment transport capacity of overland flow decreases, promoting particles deposition. Dissolved-P retention is more dependant on contact time, kinetics and soil chemistry (organic matter, Fe oxides etc), thus having some similarities with the behaviour of other dissolved compounds such as NO3. The dissolved-P can be trapped in the solid phase (sorption, precipitation) and consequently the P storage capacity of a buffer will depend partly on the fixation capacity of it soil. These basic processes of the buffer effect for P, can develop in landscape structures that are very diverse in terms of physical state and biogeochemical conditions (marshes, hedges, grass strips etc.). The question is to determine, within a watershed, which non-constructed landscape structures have buffer potentialities and also to assess the efficiency of both non-constructed and constructed buffers?

Other important components of the buffer effect are the processes occurring during storage. Once trapped, pollutants may be stored without transformation or transformed within buffers according to their nature, biogeochemical reactivity and interactions with plants or micro-organisms. For N and C, biogeochemical processes may also result in losses from the watershed in gaseous forms. Regarding P, there is no significant loss but changes to speciation can occur (dissolved-particulate; mineral-organic). Some removal can be achieved by immobilisation in perennial biomass or refractory organic matter. Vegetation and microbiological uptake, however, are often at the origin of further seasonal remobilisation and release of a fraction of the trapped total-P (Dorioz et al 2006). Anaerobic conditions can also create high levels of dissolved-P by the reductive dissolution of ferric hydroxides carrying P.. Thus, the seasonal redox status of a soil, which depends on water residence time, water table depth and fluctuation, is an important determinant of the potential role of a buffer to sustainably retain total-P. It should be noted that soil anoxia has antagonistic effects on N and P dynamics (decreases nitrate but can generate dissolved-P, see Bidois, 1999).

All these basic processes combine to create the buffer effects which are individually as diversified as the factors controlling these processes (vegetation, hydrology, soil, micro-topography, management…)

OVERALL ORGANISATION OF LANDSCAPE INTERFACES AT THE WATERSHED SCALE

Interfaces are important components of the P transfer system (they act as buffers if they are properly structured, located and managed; if not, they ensure direct hydraulic connections between sources and water bodies). Their contribution to the transfer system depends on the objects they "join" together and the water fluxes which flow through them (table 1).

– **Interfaces between farm infrastructures and surface water**. Some landscape structures regulate the surface flow connectivity between sections of farm infrastructures, which mainly consist of impervious surfaces and produces waste water, and surface water. Mitigation options in this case aim mainly to disconnect diverse storage facilities from surface water networks which prevent or reduce the transfer of water polluted by organic matter and nutrients. One possibility for mitigation, among others, (see Stadelmann and Blum, 2005) is to introduce buffers such as a farm pond or grass filter strip.

– **Interfaces between livestock locations, pathways, and surface water**. Free and direct access for livestock to rivers, streams and ditches, is common in many regions and especially in extensive pasturing or rangeland areas. This has many impacts on the P and sediment budgets of rivers:1) direct inputs into the watercourse 2) erosion of river banks and re-suspension of sediment (Lefrancois *et al.*, 2007) and thus generation of a flux of total-P and sediment during both low- and high-flow periods. River bank erosion due to livestock can also allow direct flow connection with hillslope erosion. A manager targeting the protection of water quality aims to transform these interfaces into physical barriers between grazing animals and hydrological network (Meals, 2004). This can be achieved by: 1) fencing off 2) organizing livestock stream and river crossing through specific bridges or paths; 3) relocating gateways of pastures away from watercourses and if possible, from down- to up-slope.

– **Interfaces controlling the connectivity between emitting fields and surface water**. Considering P mobility and dynamics in the environment, interfaces can be differentiated according to the local hydrological and biogeochemical conditions.

(1) **Under saturated conditions** (very shallow groundwater) there are wetlands. They are often located in the lowlands of headwater watersheds, scattered in the rural landscape and often associated with wet meadows. The riparian wetlands, situated along the surface water boundaries, control the inputs from fields to surface water. Some head-water wetlands are in-stream wetlands (inserted within the hydrographic network); they modify the signal emitted by the corresponding watersheds. Maintenance and/or restoration of wetlands are part of the objective of water quality programs, but their attenuating effects on P are still discussed.

(2) **Under unsaturated conditions**, hydrographic network boundaries and field boundaries represent highly diversified interfaces (including constructed buffers, fragments of non-cultivated land, technical spaces…). Under certain conditions they can limit sediment and nutrient transfer from emitting fields to water bodies. Along permanent streams and ditches there are riparian strips (or areas). The objectives are to assess the potential of an individual riparian interface to have a buffer effect and to transform some of them into buffers or to create vegetated buffers instead of ineffective boundaries. The objectives are similar with inter-field boundaries: they control the connectivity of surface runoff, from plot to plot and thus have special importance in the initial step of the propagation of diffuse flow.

BUFFER CAPACITY OF WETLANDS

Small wetlands (typically <10 ha) incorporated into agricultural landscapes, often form interfaces between intensively cultivated hillslopes and plateaux and the water bodies. They often play a major role in the dynamics of exchanges of water and matter between water body compartments and between land and aquatic ecosystems (fig 2).

The efficiency of wetlands at reducing nitrate pollution has been intensively studied (see eg. Machefert and Dise, 2004). Beaujouan *et al.*, (2002) have demonstrated that the length of contact between the wet zone and the contributing area of nitrate, is a major factor in their efficiency regarding nitrogen abatement. Thus a narrow width can be adapted to function as a biogeochemical buffer (Mitsch and Gosselink,1993). Shape, topography and organisation also seem to modify the wetland's effect on total-P transfer, but in a different way.

First of all, all wetlands can trap particles and many individual studies have shown that natural wetlands can, consequently, store some of the total-P emitted from upstream fields (see e.g. Reddy et al, 1999; Uusi-Kämppaä et al 2000). Other experimental results have suggested that wetlands are potential buffers for total-P: P removal has been observed, at least for short term retentions, in natural wetlands used as waste water filtration systems and in artificial wetlands constructed to deal with runoff from fields (Carty et al., 2008).

Three conditions need to combine for total-P retention in a wetland: 1) particulate-P of incoming fluxes decants because of the slowing down of water; 2) dissolved-P is reduced by biological uptake and 3) by some geochemical processes, mainly

precipitation (Ca/P and/or Fe/P). Sorption is also mentioned as an important process, particularly in artificial wetlands literature. Absorption by plants and microbes creates short term sinks, with the exception of the incorporation of a fraction of total-P in refractory organic matter of peat (longer sink). Plants in wetlands often have a high P content, and harvesting is a way to remove some P (in some traditional French agricultural systems, biomass from certain wetlands was harvested and used as a litter for livestock, ensuring a return of P from wetlands to the farm fields).

We monitored a very efficient buffer wetland of 2 ha, situated in the Lake Geneva watershed (France, Dorioz and Ferhi, 1994). This case study helped us to understand the key factors of efficiency. At the annual scale, the pilot wetland stored 2/3 of total-P inputs brought by a little stream (Q from 0.1 to 100 $l.s^{-1}$). This represented retention of about 7 kg total-$P.ha^{-1}$. A slight selective effect was observed (60% of retention for dissolved-P and 78% for particulate-P). Considering individual hydro-meteorological periods over a year, we showed that the efficiency tended to be greater with higher-flow event inputs (fig.3) and that the wetland functioning was close to that of an "attenuating filter" (fig.1b). Moreover, transfer within the wetlands led to an important change of particulate-P speciation, as indicated by a comparative study between sediment trapped at the outlet and the inlet (table 2). For the same total-P content, outlet sediments showed a change of the two main P mineral fractions (increase of P extractible by HCl, considered as Ca bounded P, and decrease of P extractable by NaOH considered as Fe bound P), much lower bio-P content, and an exceptionally high fixation power. These drastic differences and the P mass balance, suggest that the wetland introduces a major discontinuity in the total-P transfer dynamic in relationship with: 1) a sufficient water residence time; 2) a diffuse hydraulic connection between inputs and outputs; 3) a consecutive spatial differentiation of functioning within the wetland (sedimentation occurring in the inlet areas, chemical precipitation near the outlet, and biological uptake in the intermediate and largest area). We assume that the efficiency observed in P retention is due to such an organisation and functioning.

The diversity of wetlands in a landscape is very great and as such, individual studies may not be justifiably extrapolated to wetlands in general. Wetland functioning varies with micro-local conditions (shape, vegetation topography, micro-hydrology…) and also with seasonal and hydro-meteorological conditions. In the landscape area including our pilot wetland, we described all of these micro-conditions for wetlands on a gradient from small (<0.1 ha) endoreic wetlands acting as a barrier for surface runoff and total-P, to larger ones acting either as attenuating filters (but more or less leaking during higher flow events). Moreover, despite sedimentation occurring in all wetlands, some of them may be less effective (or sometimes ineffective) in attenuating total-P because of re-mobilisation of particulate-P due to erosion of the wetlands along the flow pathways and/or release and export of dissolved-P (released by reduced iron compounds). This latter phenomenon needs anaerobic conditions which could be permanent or seasonal according to the wetland type (Khalid *et al.*, 1974).

The watershed scale adds complexity: multiple site specificities, interactions between diverse types of functioning, connectivity between wetlands and water bodies (fig 2) and the effect of position within the watershed. Using a landscape approach to study the overall attenuation of diffuse-P pollution in a Lake Champlain sub-watershed (USA, VT), Wang *et al.* (2004) has defined characteristics of the wetland buffer effect on a watershed scale:

(1) wetlands as a whole or as a general land cover type, are significant elements of the landscape buffer capacity for total-P (evaluated to 30%);
(2) P removal is highly variable within a watershed (comparison of a significant set of inlets and outlets during a spring snowmelt, indicated that the net flux was positive for 30% of the sampled wetlands and negative for the other 70%);
(3) landscape position (stream order) modifies the intensity of effects.

The overall message is: although wetlands are diverse in nature, structure and function, their preservation is positive regarding mitigation of P losses. Some management can be done to maintain, improve or restore their efficiencies as buffers. Available knowledge on the working of P-efficient pilot wetlands, gives a framework to advise this management: increasing incoming fluxes from the hillslope (e.g. redirecting drainage water), controlling internal water pathways in order to increase residence time in wetlands and decrease flow velocity and, finally, harvesting biomass to limit P stocks.

Management and artificial transformation of wetlands must also consider some uncertainties concerning the long term saturation of wetland buffers. One can assume that they will be filled with sediment and P, and become ineffective or worst become a source of P. Wetlands used to treat wastewater provide an extreme case of very rapid saturation, turning the sink into a source.

BUFFER CAPACITY OF INTERFACES IN UNSATURATED CONDITIONS

Under unsaturated conditions, vegetative buffers are typically constructed devices along reaches of hydrographic networks, with a strip feature. These constructed vegetated buffer strips have been widely studied and represent a quite well known, tested and calibrated "model". By comparison with this model, it is possible to evaluate the potential buffer effect of non constructed interfaces, particularly of the various landscape entities constituting riparian boundaries or boundaries between farm fields (table 2). If properly structured, managed and situated, all interfaces can contribute to water preservation at the local level. They can also have an effect at the watershed level, modifying the flow regime in the stream, particularly by a decrease of the peak flow and thus the erosion directly related to discharge, such as river bank erosion.

Lessons learnt from constructed vegetative buffer strips

Constructed buffer strips are generally considered to offer an efficient protection against total-P. Hoffmann *et al.* (2009) have reviewed the efficiency of riparian buffers for total-P retention and quantified the reduction of outputs as 41 to 93% (as a percentage of the inputs). The same order of magnitude is given by Dorioz *et al.*, (2006) for particulate-P in grass filter strips. The constructed buffers are rarely 100% effective under experimental conditions (which are generally chosen to be a realistic representation of farming systems). Regarding fluxes, riparian buffers may account for total-P retention rates of up to 128 kgP $ha^{-1}.yr^{-1}$, and plant uptake may temporarily immobilize up to 15 kgP $ha^{-1}.yr^{-1}$ (Hoffmann *et al.*, 2009). This can be compared to the 1 to 2 kgP $ha^{-1}.yr^{-1}$ exported on average by tilled fields. Retention of dissolved-P in riparian buffers is lower, often below 0.5 kgP $ha^{-1}.yr^{-1}$, several studies have shown a significant release of dissolved-P of up to 8 kgP ha^{-1} yr^{-1} (Hoffmann *et al.*, 2009).

Functioning

The buffering effect of vegetative buffer strips results from a group of phenomena which are triggered during runoff periods, and are the consequences of the hydrological and biogeochemical properties of the zone. Buffer strips have an initial effect on surface runoff flowing downslope over a rougher and more porous surface than upslope, causing it to slow down (fig4a, compartment 1, 2) and infiltrate the soil. Infiltration leads to the injection of dissolved-P and other dissolved nutrients carried, into the soil mass (fig 4 a, compartment 3). Flow through the leafy matrix of grass and herbs covering the soil of the buffer, causes a complementary process of "filtration" (or "turbulent filtration" fig4a compartment) 2) which seems to be efficient in retaining small size particles (Munos-Carpena *et al.*, 1999;). All of these processes combine to reduce the sediment transport capacity (fig4b). Excess particles are progressively sedimented and trapped. Much of the P transported to watercourses being bound to particles, sedimentation is the main physical process occurring within buffer strips.

The specific hydrological properties of buffers are generally linked to: 1) a continuous soil coverage by plants, hence a greater resistance to surface flow and a decrease in flow velocity; and 2) a denser and sometimes deeper root system, which improves soil structure and increases the permeability of the soil. The infiltration, as a result of dense rooting brought about by perennial vegetation and particularly grass species, is often considered to be the main factor in the reduction of overland flow, and thus of deposition of particles.

Particulate-P and sediment are mainly stored in soil surface layers (0-5 cm). The coarser sediments, including soil micro-aggregates (Trévisan and Dorioz, 2001) and a large part of the total sediment, is deposited at the front edge of the filter

strip and also accumulate in the final metre of the emitting field (fig 4a, compartment 1). This illustrates the importance of the upper boundary in the functioning of the buffer. Sedimentation through the buffer is selective. Consequently, in some cases, output is made up of the finest fraction of particulate-P, which is also the most bio-available.

Between periods of rainfall, several important processes occur that restore buffer properties (Dorioz *et al,* 2006). Water is evapo-transpirated which renews the water storage capacity of the soil. Deposited sediments are stabilised thanks to entrapment by fine root growth, and/or re-aggregation of fine particles in larger, water stable aggregates. Dissolved-P is actively fixed by soil constituents and biota, and thus remains in the surface layer (these reactions are reduced during cold periods and perhaps universally in the colder climates). Finally, intercepted total-P is partially taken-up by plants and microorganisms and this can lead to release of some portion of P (Stutter *et al*., 2009). Release processes are regulated by physical and chemical conditions of soils: temperature, drying/rewetting and freezing/thawing, pH and organic matter dynamics (Sharpley and Tunney, 2000).The same kind of processes controls the long-term efficiency of buffer strips. Accumulation of sediment over the years tends to modify the surface state of the soil (micro-morphology and permeability) and increase the P content of the surface soil of the buffer. Finally, the storage compartments (1,2 fig4a), if not properly managed, may be saturated and thus the buffer could become ineffective, or even a source of P.

Key factors controlling effectiveness

Individual buffer strip effectiveness (input/output balance) depends on the interactions between two categories of factor (Schmitt *et al*., 1999; Eck, 2000): 1) internal factors (size, slope, soil permeability, vegetation) which regulate the residence time and infiltration rate of water, and have been the subject of many of experiments, and 2) external factors (emitting field, location…) which control the properties of incoming flows (surface/subsurface; concentrated/diffuse; P loads).

Dimensions of the buffer. Retention of total-P being the result of phenomena which develop in space, the buffer width, or the width weighted by the slope, are often considered by Extension Services to be the main factor controlling efficiency of vegetated buffer strips. However, experiments have tended to demonstrate that there is no clear universal relationship between total-P sequestration and buffer width. Within a given buffer strip, the effectiveness does not increase linearly with width (e.g. Dillaha *et al*., 1989; Castelle *et al*., 1994). Several reviews comparing sets of experiments conclude that the results of effectiveness are very scattered for both sediment and total-P retention (Schmitt *et al*., 1999; Dorioz *et al*., 2006; Liu *et al*., 2008; Hoffmann *et al*., 2009; Collins *et al*., 2009). Thus, compilation of experimental results obtained with 10 m strips, gives a retention of total-P ranging from 40 to 100%. Extremes seem more defined: with a width of < 3 m the retention of total-P is rarely more than 60%, and a 100% performance needs generally more than 8 m. Finally very large strips (such as 20-40 m) do not systematically ensure 100% retention (Castelle *et al*., 1994).

The scatter in the percentage of total-P retained at a given width is the result of several sources of variability: methods (monitoring tends to be different from an experiment to another), other internal factors (most importantly vegetation, see next paragraph) and the nature of the incoming flow. All authors agree that this latter point is critical: an optimal functioning of vegetated buffer strips needs uniformity and regularity of pollutant input flows (Bidois, 1999; Uusi-Kamppa *et al*., 2000). In most cases where wide buffer strips have been found partially or totally inefficient, the reason were attributed to the conditions of flow entering the buffers; this is generally spatial (concentrated surface flow), but also temporal (high flow velocity, snowmelt…). Inversely, a good retention rate has been obtained even with quite narrow strips, when the input surface flows were diffuse. This suggests that the dimensions of a constructed buffer strip should be modified according to the nature of the input flows, and thus according to the position within the watershed or to agricultural practices encouraging this type of flow.

Vegetation is another source of variability. The plant coverage has a secondary role as long as the minimum requirement of plant coverage (60-70%) is realised (Rogers and Schumm, 1991). It can be grass or a mixture of natural vegetation including grass, and/or trees and bushes: the efficiency of the filter depends more on plant coverage of soil than on the vegetation type (Dorioz *et al*., 2006). However trees and shrubs are more stable over the long term and signify a more sustainable landscape management (Michaud A. IRDA, Pers. Com.). Management of vegetation is another important factor

to consider. A close cut is preferable as it avoids the creation of preferential routes for runoff, and ensures a plant growth dynamic able to stabilise sediment deposits. Enhancing plant uptake of solubilised P would provide a possible loss pathway via vegetation removal. Loss rates of 4-15 kgP $ha^{-1}.yr^{-1}$ have been documented through biomass removal (Hoffmann *et al.*, 2009). Buffer biomass harvesting is a recommended strategy for many agri-environmental schemes in America and Europe. Finally, vegetation management could be a critical factor in the long-term, in manipulating buffer conditions to remove stored P, increase buffer strip lifespan and prevent P leaching losses.

Vegetation also means root systems and indirect action on soil properties. Perennial herbaceous vegetation has been recognized to have the best potentiality (Schmitt *et al.*, 1999) because of its well known influence on soil structure and consequently on soil permeability. Roots can also theoretically have an effect on subsurface fluxes but this is not well documented for dissolved-P. The root system of the trees might be more efficient because it can take up water and some chemical compounds from shallow groundwater (up to a few metres deep) and thus have an effect on the subsurface flow in some cases, whereas the grass system cannot. This underlines the specific interest to test hedgerows effects on P.

Design decision. The uncertainties of scientific evidence for effectiveness of buffer strips, in terms of total-P sequestration, makes policy decisions on buffer design rather difficult. The standards should at least include: 1) a continuous perennial vegetation coverage; 2) a vegetation management and harvesting; and 3) a width modulation according to the nature of the surface runoff inputs (in some French regions recommendations indicate a width from 5 to 10 m with diffuse surface runoff and 10 to 15 m for concentrated surface runoff, see Gril *et al.*, 2009; CORPEN, 2007). Because of the extreme variability of the landscape, new buffers, still to be constructed, should be designed within these criteria, but adapted for site-specific conditions (Correll, 2005).

Assessment of buffer capacity of non constructed landscape interfaces

Most of the landscape interfaces are not constructed buffers. Because of the extreme variability of these non-constructed interfaces (table 2) the assessment of their potential buffer effect is never easy. Measuring the individual responses (input/ouput) of all of these diverse elements, for example in a given watershed, is rarely possible. Fields indicators are needed. They can be extrapolated from experiments on constructed vegetated strips considering that the same structure means the same function and that key factors of efficiency are the same for all kinds of interfaces. On that basis,a non-constructed interface which introduces a significant change in conditions for surface runoff and infiltration, due to its roughness, vegetation, permeability and size, can reasonably be considered as a potential buffer for total-P. Table 3 presents the main characteristics used to identify, with a visual and soil expertise, these potential buffers in our pilot areas of Lake Geneva basins.

We applied such expertise in a rural sub-basin of 3000 ha. The studied landscape is heterogeneous (Wang *et al,* 2004) and a range of landscape structures existing in unsaturated areas were identified as potential buffers (semi-natural riparian vegetations, field margins, hedgerows…of varying width). Among them, we observed that well located hay fields (inserted between a source of P and a reach of the hydrographic network) often created very efficient buffer effects (acting as a barrier). This supports the idea that a mixture of land cover and land use is advantageous regarding attenuation of P transfer. Faced with the diversity of landscape interfaces structures, we created a typology which classified them according to their permeability, dimensions, soil, into 3 classes of potential buffer capacity: no buffer effect but protection against stream bank erosion, attenuating filter and barrier.

The typology was also used to categorize all of the landscape interfaces in several sub-watersheds, which were finally characterized by the % of tilled fields buffered by an efficient interface (attenuating filter or barrier). Considering that this % was a reasonable measure of the overall buffer capacity of a given agricultural area, we showed that this property of sub-watersheds was highly variable and mainly related to human factors. Most of the buffer capacity due to interfaces was generated and managed by a few types of farming system (traditional dairy farming systems) while, on the contrary, some more intensive systems tended to increase surface runoff connectivity. Surprisingly, the technical conditions favorable to

implementing and constructing new buffer strips were found only in some intensive farm types. Finally, management of non-agricultural land appeared also to be crucial and biophysically induced discontinuities (often corresponding to boundaries of sections of forest) were, overall, a secondary factor.

Efforts will be made to validate our typology locally. This could be accomplished first by a set of experimental studies aimed at calibrating the most typical landscape interfaces identified. Initial results have provided evidence that some hay fields identified as buffers can responded to incoming total-P fluxes by retention (Trévisan and Dorioz, 2001). At the watershed scale, we envisage, using a comparative study of a set of agricultural sub-watersheds, to test the correlation between landscape organization (with descriptors including the typology of interfaces) and some expression of P fluxes at the outlet (similar to the "landscape approach" used by Wang *et al.*, 2004 for wetlands).

Specific buffer capacities of inter-field boundaries

In an agricultural landscape made up of a matrix of small fields, like in our alpine lake basins (mean size of individual fields, 1-2 ha), inter-fields interfaces have a specific importance because they – even the narrow ones – can prevent the concentration of surface runoff and thus: 1) contribute to limiting cascading effects of erosion from field to field; and 2) increase the performance of the down-gradient vegetated buffers. Consequently in our landscape system, they were considered as a critical location for buffers.

Whatever their initial detailed features, inter-field boundaries can be managed to become efficient filter strips. Recommendations for improvement and maximisation of existing interfaces are based upon the same kind of diagnostics as the assessment of interfaces, previously presented. Gateways often represent a specific point of interest because they are breaks in the boundaries and thus are critical areas for surface runoff in all kinds of fields (tilled fields or pastures). Ruts from tractor wheels tend also to converge and can channel surface water to these areas. At the landscape level gateways, livestock and tractor pathways represent a network of preferential flow pathways that hydrologically connect fields situated up-slope to down-slope and finally to the water course. Relocation of gateways, if possible, from down to up-slope is a simple way to decrease local and global hydrological connectivity, thus reducing this source of P pollution.

In some regions, the networks of interfaces between fields are made up with hedgerows ("bocage" in Brittany France) which means planted with trees, with or without a bank. Intense watershed studies have shown that the influence of these structures at that scale on the flow regime of streams and rivers (Mérot 1999; Viaud *et al.*, 2005) decreases the peak flow by modifying surface, subsurface, and inter-storm flows, and modifying evapo-transpiration from the watershed, therefore contributing to a decrease in the erosion of the river bank and flooding. We can reasonably assume that this will also reduce total-P transfer, at the watershed scale.

DISCUSSION – CONCLUSION

Diffuse-P transfer is a landscape-level phenomenon involving the complex diversity of landscape components that governs flow paths and the spatial distribution of sources, connections and buffer effects that make up the transfer system (Wang *et al.*, 2004). Buffer effects influencing total-P transfer occur in many kinds of natural or semi-natural landscape entities and in constructed devices. All buffers have the capability to both, decrease the suspended-matter transport capacity of surface water flows and to store water and particles, thus increasing their residence time and allowing further biogeochemical processes to develop. This potential for attenuation is obtained each time surface or subsurface water flows through hydrological discontinuities due to certain types of soil-vegetation and/or topography. Total-P can be easily and efficiently trapped, even during short and relatively rapid transfer, via sorption of dissolved-P and physical retention of particulate-P. Dissolved-P is more sensitive to contact time, kinetics and soil chemistry. Trapping generates storage in sediment, soil, and biomass, preventing or delaying, the export to sensitive water bodies.

Construction of buffers has been largely promoted as an efficient tool for reducing the transfer of suspended matter, pesticides and nitrogen to waters bodies (Patty *et al.*, 1997) and, in Europe, often sustained by financial compensation. Recommendations to employ constructed buffers to control diffuse total-P transfer have also become very popular among lake managers. But there are several issues for the assessment of the buffer effects on total-P, and this contributes to some uncertainty in the capacity and design of buffers. Moreover, land managers has not paid enough attention to non-constructed landscape buffers (particularly hedges, field margins, hay fields) whose beneficial effects on total-P transfer exist but are difficult to quantify. All this illustrates the need for better conceptual and operational tools.

Since the long-term functioning and eventual saturation of constructed buffers are not yet well documented, there is an initial uncertainty about the sustainability of buffers regarding total-P. As no loss pathway exists for P, it is unlikely that retention can be infinitely sustained (Stutter *et al.*, 2009). Sustainability is driven by the processes occurring after the initial trapping phase and can limit, over the relatively long term (years), further mobility of accumulated total-P. That limitation depends largely on the management of vegetation and soil surface and conditions. Anoxia and/or dead organic matter accumulation on the soil surface (corresponding to plant uptake), leads to dissolved-P releases, which can limit or nullify the buffer capacity. In the same way, the accumulation of diverse contaminants within the same storage location is not necessarily positive. As an example, dissolved-P release has been observed in wetlands receiving excessive fluxes of NO_3 (Paludan, 1995).

Diversity and common denominators. Buffers usually appear to provide useful short-term functions in the attenuation of diffuse phosphorus pollution, despite the extreme diversity of landscape contexts and structures, which explains the variability of individual performance. The performance of buffers varies largely according to a set of interactive, internal and external factors – a complexity which limits our capability to extrapolate the buffer capacity of a given landscape buffer from experimental results. In fact, the multiplicity of factors driving buffer capacity being thus, each study of an individual buffer tends to be site-specific and scale-specific even for quite well-known and tested models like the grass vegetated buffer strips (Dillaha and Inamdar, 1997). However, fortunately there are only a few common limiting factors. These can be used to indicate whether a buffer effect can, or cannot, be reasonably expected in a given landscape structure. For example, in unsaturated areas, buffer effects, require first of all, a minimum width, permeability and soil coverage, with these dimensions having to be modulated according the nature of flow inputs (diffuse/concentrated). This latter characteristic controls the eventual existence of preferential pathways for surface water flows within the buffer. This characteristic is also an important indicator of the functioning of wetlands.

Watershed scale. The watershed scale adds a lot of complexity, and our understanding of the overall buffering capacity for P is limited. Firstly, the transfer system includes not only sources (emitting discharge/concentration inputs signals) and buffers (transforming these signals): many landscape elements between sources and water bodies function just as connecting media. These are generally and implicitly considered as neutral components, transferring the input signal without modifying it. But we should pay attention to other situations: 1) some connecting interfaces can become critical areas for erosion, if not minimally vegetated and managed (e.g. banks damaged by tilling); and 2) direct field-to-field connections can facilitate concentrated runoff and consecutive cascading erosive effects. In the latter case, the absence of a buffer is not neutral, but rather means an increase in the signal intensity and difficulties in controlling diffuse transfer.

Buffers have also to be evaluated with respect to scale and landscape connectivity (e.g. Verstraeten *et al.*, 2006). Within a watershed, buffer interfaces represent very diverse entities but with similar function with regard to total-P attenuation. In heterogeneous landscapes, they are often organized as a network characterized by: 1) connectivity; 2) distribution related to slope, vegetation and local hydrologic gradients; and 3) management practices applied on these pieces of land (a given structure acts as a buffer only if properly managed).

Within this network, the efficiency and nature of buffer responses tend to be distributed spatially as a function of the organisational level of the watershed. Fig 5 illustrates this idea using as a reference the landscape organisation observed in the Lake Geneva rural area. Buffers acting as real barriers (as defined by Viaud *et al.*, 2004) tend to be located in places corresponding, to short and relatively rapid transfers, which means sheet surface flows, temporary inputs, and to unsatu-

rated areas (no release). Such efficient buffers (no ouput signal exept background level), constructed or otherwise, are usually located at field boundaries (often vegetative strips or hedgerows). Once the surface water flow is concentrated, barriers are rare (they might be very wide); consequently the buffers existing at this level of organisation mainly function as attenuating filters (leaking vegetative strips or riparian wetlands), with different degrees of efficiency for total-P, and a selective effect for bio-available P and dissolved-P. At the upper level of organisation (sub-watershed, stream order 1 and 2) in-stream wetlands functioning as attenuating filters are the only type of buffer possible. Finally at the basin level, buffer effects become limited to trapping particulate-P in flood areas (an "attenuated barrier" according our classification). The in-stream processes associated with biota and sediment delay the transfer but their environmental benefit has to be demonstrated (Dorioz et al 1998). Thus the buffer network has a hierarchical organisation typical for P transfer system and corresponding to a decreasing gradient of efficiency from the fields up to the basin level (the dynamic would be inverse for NO_3).

Maximizing the buffer effect: "critical buffers". Since the position of the buffer interfaces within the watershed is one of the major drivers of their efficiency, it is generally considered that the placement of improvements of buffer capacity of interfaces or/and the construction of new buffers, must be done in hot spot locations, such as in bottom field corners, gateways…. This means that careful selection of buffer features is required in critical areas, depending on the local hydrological situation. An example of the latter point would be the selection of grassed buffer strips for sheet flow, but bunds and constructed wetlands for convergent flow paths. Other decisions also have to be made, such as whether to target hot spots with wider buffers (Vidon *et al*., 2010), or a uniform system of narrower buffers applied everywhere (e.g. 2 m riparian buffer strips) preventing surface flows to be concentrated. This can be solved differently according to the rainfall regime and thus climate. Special attention should also be paid to situations where no buffer would mean a cascading effect (e.g. inter-field buffers).

In the limited space of many European agricultural areas, buffers still need to be proven to work, to ensure their existence and implementation. However, the lack of data and models that we have mentioned is not sufficient to deter the incorporation of all categories of buffers into landscape management. Buffers should be maintained, constructed and used despite their limitations and as part of the general strategy for the control of phosphorus diffuse pollution.

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