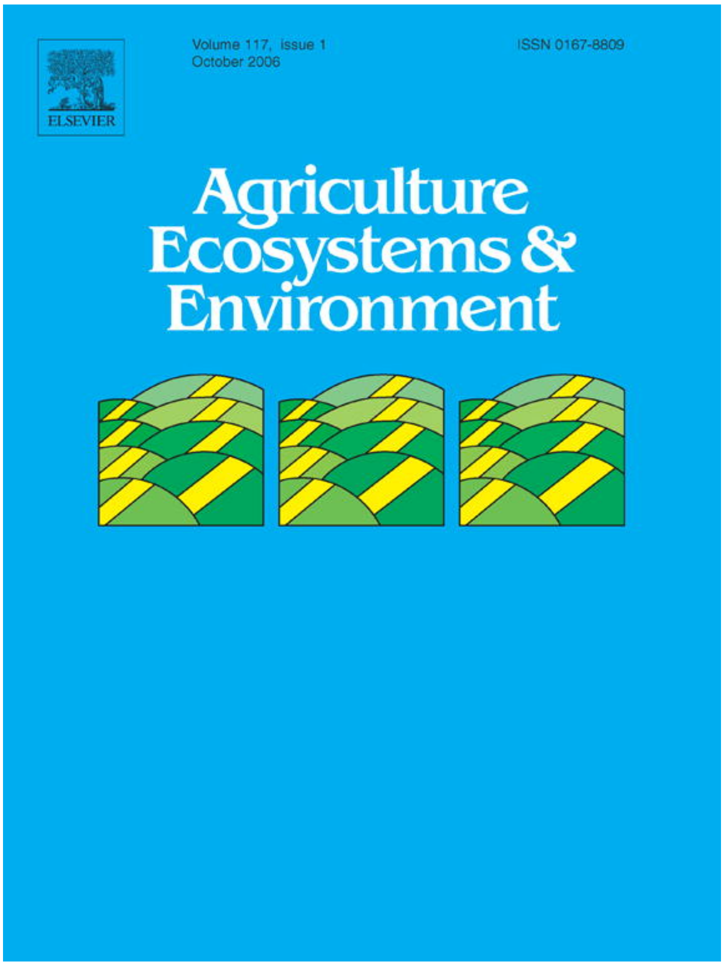
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Review

The effect of grass buffer strips on phosphorus dynamics—A critical review and synthesis as a basis for application in agricultural landscapes in France

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Abstract

Recommending the use of ‘‘grass buffer strips’’ to control diffuse P transfer has become well accepted among extension advisors, agricultural consultants, planners, and other practitioners that influence the structure of the agricultural landscape. These grassed areas are put in place to capture the P contained in runoff from source fields. They are designed to function as a filter and a sediment trap although it is often unclear what the long-term disposition of the accumulated P may be. The objective of this work was to determine if the available scientific literature justifies the continued recommendation of this approach in the prevention of phosphorus movement from agricultural soils to surface waters. We employed a theoretical analysis of the mechanisms of the buffering effect and the specific behaviour of phosphorus in typical grass buffer strips to establish the critical set of literature applicable to this question. An adequate body of literature exists describing many aspects of P dynamics and the short-term functioning of grass buffer strips over their seasonal cycles. Despite variable results in a diversity of landscape contexts, overall, the use of grass buffer strips appears to provide useful short-term functions in the reduction of P transport to surface waters. Long-term benefits remain questionable given the relatively short-term use of this approach in P reduction and the lack of long-term experimental results, but this current lack of data is not sufficient to deter the continued incorporation of grass buffer strips in the landscape of French agricultural. Additionally, a more comprehensive conceptual model integrating the short-term functioning of grass buffer strips with seasonal cycles and the long-term consequences of cumulative storage emerged from our synthesis.

Keywords: Phosphorus; Diffuse pollution; Grass buffer strip; Agriculture

Contents

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1. Introduction

Diffuse pollution is a major threat to surface waters, especially in the context of eutrophication caused by agricultural phosphorus (Sharpley, 1995; Daniel et al., 1998). Nutrients and pesticides/herbicides/biocides are transported both in drainage through soils and in surface runoff over soils resulting in a complex and diffuse, large-scale movement of pollutants that is difficult to control. In addition, large volumes of water and sediment accompany these pollutants which, together with the unpredictable nature of the flux, makes technological treatment of diffuse agricultural pollution in streams and rivers unrealistic, except under very limited circumstances. Thus, management of diffuse fluxes must be undertaken strategically, employing integrative approaches that coordinate control processes from the scale of the individual field to that of the entire catchment area. Only through consideration of the cumulative effects of diffuse pollution at multiple scales can this growing problem be ultimately addressed.

The strategy for the control of diffuse pollution thus comprises several ''lines of defence'' according to the terminology adopted by ''Institut de Recherche et Développement Agricole'' of Quebec (Duchemin and Madjoub, 2004). At the scale of the individual field, when applying fertilisers, the objective is to adjust the quantities and the timing of applications (Mandaville, 2000) to control the contents and the stock of pollutant in or on the soil at critical times and in critical zones. This limits leaching and/or surface runoff (Daniel et al., 1994; Weld et al., 2001; McDowell et al., 2001). At the scale of the catchment area, one can rely on additional methods of control including the use of buffer zones, which intercept, retain, and transform the pollutants contained in the flowing water (Vought et al., 1995; Addiscott, 1997; NRCS, 1997; Heathwaite et al., 2000; Dosskey, 2001; Benoit et al., 2004). These landscape features can function as a filter or a trap, and include components of natural landscapes such as riparian forests, wetlands, swamps, etc., as well as man-made ones, including hedge rows, water management structures such as filter trenches, or those grassed areas deliberately sown as vegetated buffers. The latter areas, also known as ''grass strips or buffer strips,'' are inserted between the agricultural fields that are the source of the pollution and the surface water that receives it, either near the edge of the field or throughout the length of the drainage network.

These grass buffer strips are mainly intended to limit the amount of surface or subsurface flow. Thus, for the past 30 years, the Natural Resource and Soil Conservation Service (NRCS) of the USA (Magette et al., 1989; Gril et al., 1997; NRCS, 1999) has recommended the systematic planting of such grass buffer strips downstream of erosive fields and alongside ditches and rivers. This kind of policy was first applied in Europe when implementation of the Common Agricultural Policy resulted in the subsidy of the planting of grass buffer strips along river banks as part of its set-aside policy.

The efficacy of grass buffer strips in erosion control and the control of pollutants has already been the subject of numerous studies, which generally show a positive effect on reducing the transfer of suspended matter, pesticides, and nitrogen to surface waters (Gril et al., 1997; Patty et al., 1997; Harris and Forster, 1997; Souiller et al., 2002; Aora et al., 2003; Dutertre et al., 2003; Benoit et al., 2004). For nitrogen and most pesticides, retention in a grass strip is accompanied by biogeochemical transformations that tend to reduce the quantities present over time through denitrification, degradation, decomposition, etc. This explains the general efficacy of this kind of buffer system.

The dynamics of phosphorus in similar conditions is necessarily different because no biogeochemical transformation is able to reduce the quantity of P stored within the buffer. Thus, phosphorus can accumulate in the buffer strip until its concentration is so high that the soil and vegetation can no longer store additional P. Despite the inability of grass buffer strips to function as a component of a long-term strategy for phosphorus reduction, recommendations to employ grass buffer strips to control diffuse P transfer have become very common among land managers. Thus, it is timely to examine the available scientific literature in order to justify the continued installation of this type of buffer and establish its limitations in application. Hence the objective of this work was to define a critical set of literature that is based on a theoretical analysis of the biogeochemical processes influencing P dynamics in human-dominated landscapes. This literature was then used to evaluate the overall role of grass buffer strips in reducing phosphorus transfers from agricultural soils to surface waters.

Specifically, we were interested in the ability of experiments and models reported in the literature to provide a mechanistic framework for understanding the unique attributes of P dynamics in soils and water within grass buffer strips. Starting with a more general approach, we examined the extensive literature focused on the short-term functioning of grass buffers strips with respect to water and all its constituents (e.g., N, P, sediment, toxics). We included observations on changes in dynamics over seasonal cycles and measurements and interpretations about long-term cumulative effects to provide a more comprehensive approach. This synthesis laid the groundwork for conclusions about the efficacy of grass buffer strips in the specific context of phosphorus reduction. We then considered the practical application of these buffers in the real working landscape of France, paying particular attention to the (1) special biophysical conditions in the regions where P is a concern and (2) the social realities of current modes of agricultural practice.

Our analysis begins with a three part theoretical framework: (1) what is a buffer effect and how can it be evaluated, (2) how can the specific biogeochemical behaviour of P in its various forms affect P dynamics under conditions associated with movement across buffer zones, and (3) how can we conceptualize and compartmentalize the functioning of grass buffer strips with respect to P storage at different time scales.

2. Theoretical framework

2.1. Defining a buffer effect

A buffering effect is defined, both in chemistry and in general, as the capacity to resist change. Applied to the question of the transfer of water, contaminants, and sediment in catchment areas, the buffering effect characterises the response of a landscape structure to the incoming flows of a given material (Viaud et al., 2004). This response is measured by the relationship between inputs and outputs, with the buffering effect being indicated by a reduction of the pollutant load or an attenuation of the temporal dynamics of the P emission beyond the buffer zone.

The main processes involved in buffering effects in catchment areas are well described (Cooper et al., 1995; Dillhaha and Inamdar, 1997; Uusi-Kämppä et al., 1997; Benoit et al., 2004; Duguet et al., 2002): control of water flows, reduction of sediments fluxes, biogeochemical regulation, and chemical transformation. All these processes can develop in landscape structures that are very diverse in terms of physical state and biogeochemical conditions (marshes, hedges, etc.). Their activity depends on the pollutant in question, its properties, and its hydrochemical behaviour, and notably its preferential hydrological transport routes.

Faced with this diversity of structures and processes, Viaud et al. (2004) proposed a new approach creating a concept of ‘‘buffering capacity’’ applicable from the field to the catchment scale. Inputs and outputs are treated as ‘‘signals’’ (flows, concentrations, or rates). Thus the metrics used to describe the buffering capacity are expanded to include signal reductions not only in mean values, but also in frequency, variability, and range. Our experience also shows that buffer zones within a catchment area can also cause temporal delays in fluxes. The buffering effect may also be distributed spatially as a function of the organizational level of the catchment area (e.g., stream order, Weller et al., 1996).

The approach proposed by Viaud et al. (2004) is well suited to grass buffer strips. These soil–grass systems receive an inflow of surface or subsurface runoff containing both suspended and dissolved matter (the ‘‘input signal’’), and release an ‘‘output signal’’ of a similar nature to adjacent surface water. However, the output signal varies in many ways from the input, with a modified concentration, flux, variation, and/or frequency. The effectiveness of the buffer depends on the time of interaction of flow within the grass strip, a key parameter that determines the retention and attenuation of pollutants in each compartment of the buffer system (Benoit et al., 2004). For P, we assumed that there is an environmental benefit if the transformation of the signal is accompanied by a lowering of the quantity and/or a modification in the behaviour of the incoming P that decreases it potential impacts on down-gradient ecosystems. Possible mechanisms are described in the next section.

2.2. The biogeochemical behaviour of phosphorus and its implications for grass buffer strips

A very extensive literature deals with nature of soil P and abiotic and biotic reactions that govern the fate of P in soils (e.g., van Riemsdijk et al., 1984; Sanyal and De Datta, 1991; Frossard et al., 1995; Sharpley, 1995; Robert, 1996; Morel et al., 2000). Our intention is not to present a review of phosphorus soil chemistry, but to highlight processes and factors that can be of prime importance for a buffer zone soil receiving various forms of P from upland sources. These processes govern the mobility of P across the buffer zone soils and consequently influence the dynamics of dissolved-P (retention and release).

2.2.1. Nature of P and key processes of transformation

Soil P exists in many forms, some quite complex and difficult to quantify precisely. P is found in organic and inorganic form, which are distributed throughout the solid and aqueous media and living tissue that comprises the soil. Inorganic P exists in solution, is sorbed at the surface of soil particles (e.g., metal oxides, clay, minerals, $CaCO_3$ particles), or is precipitated as secondary minerals, mainly with Ca, Al, or Fe. P is also associated with primary minerals in the fine and coarse fractions of the soil. The proportion of P in soil solution is very small but much more chemically and biologically active.

The overall distribution of P is a result of a series of physico-chemical and biological processes that determine the exchange dynamics among the pools (Sanyal and De Datta, 1991; Frossard et al., 2000). Sorption–desorption and dissolution–precipitation are the main processes influencing soil and sediment inorganic P. Sorption includes relatively fast (hour to day) reversible surface reactions (“adsorption”). Once adsorbed, P can diffuse into the matrix of the adsorbent substrates, leading to stronger chemical bonds. This latter process is slower and less reversible. Dissolution and precipitation are also long-term processes (weeks to months).

Non-living organic P in soils originates from plant and microbial uptake. It includes labile forms (phospholipids, nucleic acids) and a more resistant fractions (inositol P, humic acids, Sharpley, 1995; Frossard et al., 1989; Toora et al., 2003). Interactions of organic P with soil minerals and stabilized organic matter, lead to P associated with organo-mineral complexes resistant to hydrolysis, and thus long-term persistence of organic P in soils. This slower dynamic is governed by immobilization–mineralization processes (Sanyal and De Datta, 1991). Organic P ranges from 20 to 70% of total P. Microbial biomass comprises a much smaller proportion of soil P than belowground plant biomass; however, microbial biomass plays an equally important role in soil P cycling because of its high assimilation rate and turn over rate.

2.2.2. Variables influencing P dynamics

The large diversity of P forms and structures that P is associated with in soils and sediments results in a wide range of bonding energies and exchange kinetics related to P. The resulting complex dynamics make it difficult to develop simple analytical models to predict P transfers in and out of soils. Consequently, exchanges between solid and liquid phases are described in empirical terms (e.g., adsorption isotherms for mineral P or exchangeable P, Fardeau, 1996).

When a form of P is added to a system (e.g., runoff into a grass buffer strip), the solid–solution P equilibrium is altered. The equilibration dynamics depend on time, the concentrations of the various P forms in the solution, and the particular properties of the soil. The ability of the soil to regulate this equilibration process is characterized as its fixation capacity. The fixation capacity expresses the availability of solid phase sites to trap P. The higher the fixation capacity, the greater the efficiency of P uptake and the greater the amount of incoming P stored in the soil. The fixation capacity thus depends on specific soil characteristics. The availability of sites on the solid phase to trap P is determined by the reactive surface area (clay content and type) and the availability of complexes and cations able to precipitate orthophosphate (ortho-P) in clays under different pH conditions (e.g., Ca for alkaline conditions; Al, Fe in acidic soils). Organic matter tends to decrease fixation capacity, which is therefore low in peat soils (Daly et al., 2001). This capacity is also influenced by temperature and the ionic composition of inflowing water (Sanyal and De Datta, 1991), thus leading to seasonal variations in P dynamics. In the long term, high levels of P input can saturate the fixation capacity, leading to greater P mobility and a higher risk of soluble P transfer (Sharpley, 1995).

As indicated above, the equilibration of dissolved-P in soils is not instantaneous, and it will also take some time after the initial, rapid, and reversible adsorption reactions, to develop secondary, slower reactions (e.g., precipitation and absorption) that significantly decrease both P concentration in solution and P mobility. Thus, in a system like a grass buffer strip, where residence time is short, we can expect that these short and longer term P kinetics are a critical determinant of buffer effectiveness because they can result (1) in a short-term, high, temporary concentration of P in the soil solution that increases the risk of loss in surface runoff water and (2) in the long-term, storage of P that is not readily available for reactions or transfers during future runoff events. Additional studies are needed to understand the relevance of these process in soils associated with grass buffer strips, and to characterize the variables that control P kinetics, especial factors like pH and organic matter content.

Other processes can also create high levels of dissolved-P in the soil. Under anaerobic conditions, reductive dissolution of ferric hydroxides carrying P is an important mechanism of P release (Shenker et al., 2005). Thus, the seasonal redox status of a soil is important determinant of the potential role of a soil to retain P. Dissolved-P can also originate from organic P pools and microbial pools (Stewart and Tiessen, 1987). Drying/rewetting, freezing/thawing, and associated microbial activity tend to destroy organo-mineral complexes and kill micro-organisms, often resulting in seasonal releases of dissolved phosphorus from affected soils (Perrott et al., 1990).

In summary, P storage capacity and the ability to continue to sustain this retention ability over the long term are dependent on pH, Eh, organic matter content, and seasonal soil conditions, including moisture content, redox potential, and temperature dynamics. The spatial and temporal variability in these driving variables has to be to considered in order to select places in the landscape that can reduce P transport to sensitive down-gradient ecosystems.

2.2.3. *Environmental reactivity of P*

Phosphorus is rather rare in nature when compared with its requirements by terrestrial and aquatic plants. Because of this, P is efficiently taken up into biomass and thus plays a key role in the control of ecosystems productivity. In aquatic ecosystems, excessive P results in pollution due to overproduction of macrophytes and/or algae, leading to eutrophication.

Most of the total phosphorus (total-P) stored within ecosystems is found associated with particles (particulate-P) because of its strong affinity for the solid phase. As a result, P accumulates in biomass, at the soil surface, and in the sediment compartment of aquatic ecosystems. In addition, the predominant mode of transport of P is limited to runoff (Sharpley and Rekolainen, 1997).

Only the dissolved forms (dissolved-P), and particularly orthophosphate are taken up by algae, micro-organisms, or higher plants. However, particulate-P in soil is partly ‘‘bio-available’’ as noted above, due to its physical–chemical dynamics associated with the soil solution (Frossard et al., 2000). Moreover, the particulate-P that sediments, for example at the bottom of a lake, is also not totally eliminated from the ecosystem. It constitutes a long-term source of P, remobilised by mixing or when anaerobic conditions become established at depth.

All things considered, a comprehensive evaluation of P dynamics in the environment of buffer zones, would ideally require not only an evaluation of the quantities of total-P, but also its ‘‘environmental activity.’’ This activity, including its speciation, potential bio-availability (Bio-P), seasonal mobility, etc., determines both the short-term and the long-term functioning and impact of grass buffer strips.

2.3. *Grass buffer strips: identifying compartments and their functioning*

2.3.1. *Basic physical and hydrological functioning in compartments*

The buffering effect of grass buffer strips results from a group of phenomena, which are triggered during runoff episodes and are the consequence of the interaction of the hydrological properties of the field and the adjacent buffer zone (Helmers et al., 2001). Some of the characteristic of this interaction relate to relationship of the magnitude of the mass loading (water, sediment, and associated nutrients) coming from the up-gradient field and the size of the buffer strip. A great deal of research has been done to estimate this loading in the form of soil loss equations such as USLR, RUSLE, WEPP, and SEDD, with a modest amount of success at the field scale (Moore and Wilson, 1992; Tiwari et al., 2000; Fernandez et al., 2003; Reys et al., 2004).

The runoff water reaching a grass buffer strip flows over a rougher and more porous surface, causing it to slow down and infiltrate into the soil. The changes in the properties of the environment associated with this process are linked to the presence of (1) a continuous soil cover by plants, hence a greater resistance to surface flow and (2) a dense root system typical of herbaceous plants, which increases the permeability of the surface soil layers (Magette et al., 1989; Rose et al., 2003). At the surface of the grass buffer strip, the partitioning of water between infiltration and runoff depends on the soil characteristics and on the incoming flow rate. It also depends on the duration of the event. In fact, during the course of one or a series of runoff episodes, the flow conditions may change as the soil becomes saturated and progressively silts up (Barfield et al., 1979; Hayes et al., 1979). The fraction of the runoff that infiltrates may be either stored in the soil itself (compartment 3, Fig. 1), or else it may slowly percolate to deeper layers.

The infiltration and slowing down of the water leads to a diminution of the transport capacity for solid material. The excess particles are progressively sedimented and trapped (Munos-Carpena et al., 1999). The resulting deposits are not distributed randomly. The coarser sediments are usually deposited at the front edge of the grass buffer strip (compartment 1, Fig. 1) and also accumulate in the final meter of the source field. These deposits of sediments result from the slowing down of the water and indicate that much of the peripheral interface is active in the functioning of the buffer zone. According to a study by Pearce et al. (1997), for small grass buffer strips (0.3–1 m), the majority of the sediment retained is deposited up-gradient of the grass buffer strip in small piles elongated in the direction of flow. According to Neibling and Alberts (1979) these sediment accumulations are made up of particles whose size is greater than 20 μm. Our own work (Trévisan and Dorioz, 2001) indicates that much of this sediment is in the form of micro-aggregates that are stable in water. The trapping of smaller particles, such as clay, requires ‘‘filtration,’’ a different process caused by turbulence created by the myriad of surfaces associated with the vegetation. In contrast to typical filtration, which functions through trapping material in front of pores smaller than the sediment particle size, this ‘‘turbulent filtration’’ resembles a process composed of a great many micro-centrifugations as turbulent flow passes through the leafy matrix of the grass and herb covering the buffer zone. This process seems especially prevalent further down the grass strip (compartment 2, Fig. 1).

As indicated above, the diminution in the transport capacity for solid material is accompanied by a granulo-

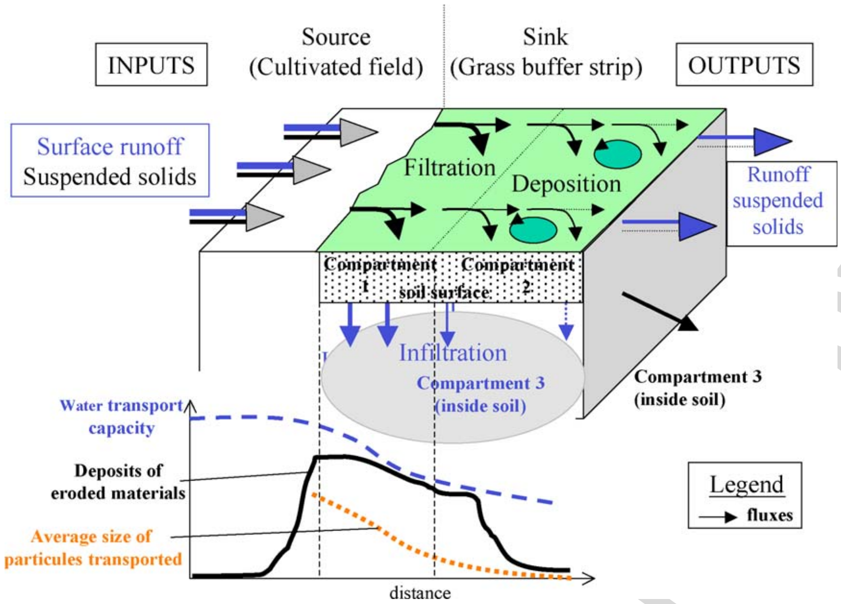

Fig. 1. Schematic representation of the functioning of a grass buffer.

metric sorting, first the coarser fractions, then the finer ones. The deposition conditions associated with the finer particles are more constrained and depend notably on the establishment of a particular flow regime favourable to turbulent filtration. Because of this, in many cases, only the coarse fractions are retained (Hayes et al., 1984; Robinson et al., 1996).

Finally, when runoff episodes follow one another too frequently, sediments deposited, but not consolidated, can be remobilised by subsequent erosion. The consolidation of deposits between periods of rainfall is therefore a critical aspect of the buffer effect (e.g., via stabilization by fine root in-growth, tillering of grass roots and shoots, re-aggregation of fine particles into larger peds).

2.3.2. Dynamics and retention of P in the various compartments

The particulate form of P dominates the flux in agricultural runoff from cultivated fields. However, the ratio of dissolved-P/particulate-P and the characteristics of particulate-P at the up-gradient edge of the grass buffer strip depend on the processes by which P is extracted from the source soil by surface runoff and on the dynamics operating during transport to the buffer zone (Fig. 2). Entering the grass strip results in a partial decoupling and separate storage of the dissolved-P and the particulate-P. This decoupling develops over a short time during flooding and is the consequence of the hydrological properties of the buffer zone. However, over a longer period, especially on a seasonal time scale, the various forms of stored P are recoupled via biological uptake, which can bring some portion of the P back into active circulation (Fig. 2). Consequently, the grass buffer strip is also an important site for the transformation of P from one form to another.

2.3.2.1. Dynamics of particulate-P. By retaining the particles, the grass buffer strip traps, at least temporarily, the nutrients that are fixed on them. This process explains most of the diminution in the load of particulate-P in the runoff. But as the sedimentation is selective, in some cases, the fraction of particulate-P fixed to the finest particles is not deposited within the grass strip (Uusi-Kämppä et al., 1997). Furthermore, the fraction of flow traversing the grass strip may cause internal erosion within the strip remobilizing P and reducing the buffer effect.

2.3.2.2. Dynamics of dissolved-P. The dissolved forms are generally completely retained by the process of infiltration (Dillaha et al., 1986a). The infiltrating water carries with it P compounds in solution. As the dissolved forms of P are actively fixed by the soil constituents, the displacement of P to depth is limited to the surface layers. P retention in this case is therefore controlled by these basic physico-chemical mechanisms. The rate of these reactions is affected by temperature, reducing the fixation of soluble P during cold spells, and thus resulting in lower retention during winter (Yli-Halla et al., 1995).

2.3.2.3. Biological recycling and transformation of P. The cumulative interception of water and nutrients, including total-P, tends to increase grass production in the buffer strip. This phenomenon has also been observed in hay meadows and hedgerows that trap runoff from cultivated areas (Parmeland, 1995) and is a manifestation of nutrient cycling in the plant–soil system of the buffer zone. Part of this recycled P may be exported in a harvested crop or released at the end of the season in a dissolved form after decomposition of the litter. All of these transformations of total-P after its retention influence the balance of the buffer effect.

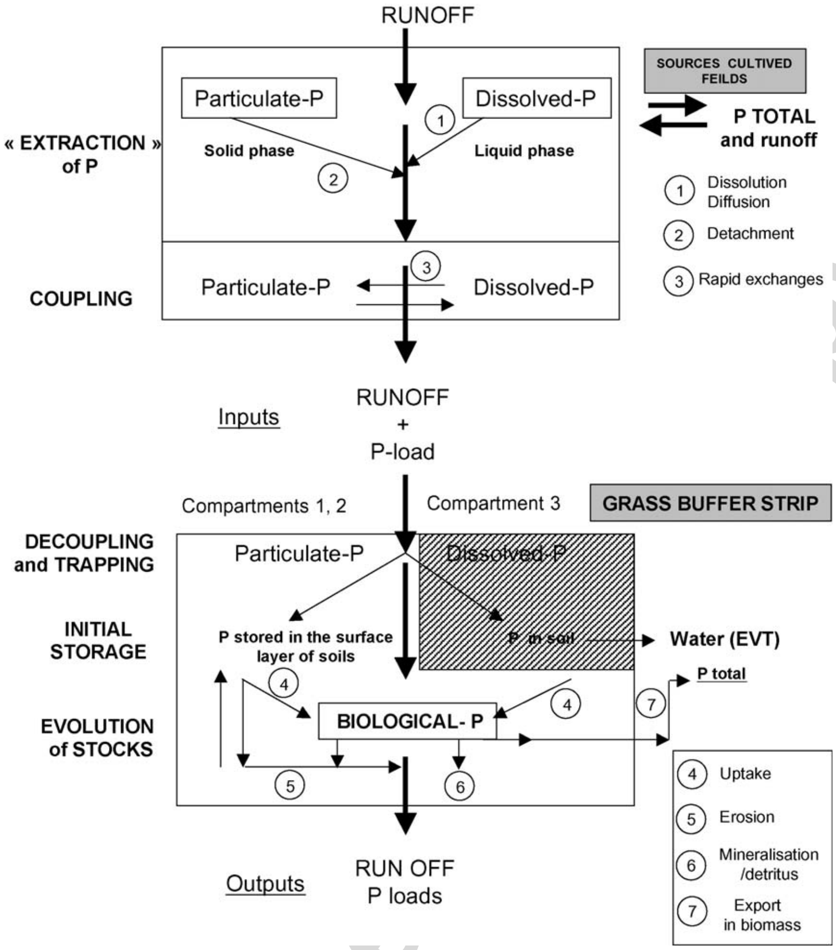

Fig. 2. Phosphorus dynamics from cultivated fields through a grass buffer strip (adapted from Lee et al., 1989).

They illustrate the importance of the integrating effect of the biological dynamics within the grass buffer strip.

2.3.3. Classification of factors controlling the retention of phosphorus

The retention of total P in a grass strip is the result of phenomena developing in space and time, hence the attention devoted to the factors affecting the surface area and the time of contact between runoff and the soil. These factors determine the input–output balance of the buffer effect and have been the subject of many experiments (presented in Section 3). They can be classified into two categories by combining the suggestions of Eck (2000) and Schmitt et al. (1999):

1. ‘‘External’’ factors, which control the properties of the incoming flow, its nature (subsurface/surface, concentrated/diffuse), and its total dissolved-P and sediment load. These factors depend on weather conditions, agricultural practices affecting the soil and vegetation, and the topography of the catchment basin.
2. ‘‘Internal’’ factors, which regulate the time for which the water is retained by the grass buffer strip and its rate of infiltration into the soil. These include topographical factors, notably the width and slope of the strip, as well as the state of the vegetation and the soil.

The relationship between the internal and external factors determines the input–output balance and thus the quantification of the buffer effect in terms of P attenuation (referred to in this paper as ‘‘effectiveness’’).

3. Effectiveness of grass buffer strips: a critical analysis of experimental studies and the expert knowledge of practitioners

3.1. An overview of applicable experimental strategies

The literature selected for review focused on the buffer processes reviewed above in the context of applicable field experiments, i.e., with field plots of variable size subjected to the action of natural rainfall (Schwer and Clausen, 1989; Schellinger and Clausen, 1992; Franco et al., 1996; Daniels and Gilliam, 1996) simulated rainfall (Magette et al., 1989; Schmitt et al., 1999; Cole et al., 1997; Dillaha et al., 1989; Abu-Zreig et al., 2003), or a mixture of the two (Syversen, 1995; Patty et al., 1997; Uusi-Kämppä et al., 2000) over short periods, from a flash flood to a year. In addition, these more critically focused studies were supplemented with experiments carried out entirely in the laboratory (Rogers and Schumm, 1991; Pearce et al., 1997). However, these experimental results are often difficult to extrapolate directly to a field environment. Finally, a few authors attempt indirect approaches based on measurements of accumulation of nutrients in the vegetation (Fail et al., 1986; Beltman et al., 2002) or of sediments estimated using tracers (e.g., using ^{135}Cs isotope, Cooper et al., 1986).

The field experiments in the literature reviewed were conducted on sites of variable sizes, involved different types of vegetation, and included a range of agricultural practices employed to maintain the condition of the buffer strip. However, in the studies reviewed, the range of these variables is compatible with local farming activities and local field patterns. The objective of each experiment was usually to design a grass buffer strip to obtain a ‘‘significant’’ retention of P. The characteristics most often tested are: (1) the load of suspended matter in runoff entering the grass strip in relation to the intensity and duration of rain, (2) the dimensions of the filter, (3) the slope of the soil, and (4) the type of vegetation (Schmitt et al., 1999; Eck, 2000). Typically, each study established a ‘‘minimum’’ level for various parameters (e.g., minimum buffer width or minimum amount of maintenance required for the buffer), or else an ‘‘optimum’’ balance between agricultural requirements and environmental desires for pollution reductions (e.g., maximizing crop production versus impact on surface waters). The extremes (e.g., very wide buffers or very steep slopes) were not tested using experimental methods.

Moreover, the great majority of the studies were made using experimental designs that only involved diffuse runoff and grassed areas in the form of strips downhill from crops. Concentrated flows and subsurface transfers have been less often studied. It should be noted that the stabilizing effect on the banks of ditches or streams, although frequently mentioned, was not generally a subject of study.

Despite the variation in the conditions for many of these studies, the overall approach employed and the similarity in general conclusions allowed some clear patterns about the effectiveness of grass buffer strips to emerge. These are described in next two sections (Sections 3.2 and 3.3).

3.2. Variations in buffer effectiveness

Effectiveness is usually expressed as reduction in output as a percentage of the input of P. In some cases, it is also reported as the ratio between an apparent reduction in an experimental treatment versus a control (for example: (OUTPUTcontrol − OUTPUTtreatment)/OUTPUTcontrol). The results of 11 studies are presented in Table 1. They suggest that grass buffer strips are able to limit significantly (>50% retention) the transfer to surface water of sediment and total-P due to diffuse flow. This function can operate

Table 1
Comparison of phosphorus retention efficiency of grass buffer strips using selected papers

Authors	Width (m)	Slope (%)	Efficiency total-P (%)	Efficiency dissolved-P (%)	Efficiency sediments (%)	Efficiency nitrogen (%)	Type of soil	Composition	Source	Flow type	Duration of the study
Duchemin and Madjoub (2004)	3 and 9	2	**85–87**	−41, −57	87 to 90	96–85 (NO_3)	Sandy loam	Grass	Cultivated land	Natural rainfalls	5 Years
Cole et al. (1997)	2.4 and 4.9	6	**–**	93	–	–	Fine loam	Mowed grass	Cultivated land	Simulated rainfall (51 mm/h)	Some rainfall events
Doyle et al. (1977)	4	10	**–**	62	–	–	Loam	Fescue and shrubs	Cultivated land with manure	Natural rainfall	Some rainfall events
Borin et al. (2005)	6	3	**80**	78	93	72	Loam	Fescue, shrubs, and trees	Corn and wheat	Natural rainfall	4 Years
Dillaha et al. (1986b)	4.5 and 9.1	5, 11 to 16	**58 to 69**	–	91 to 91	–	Loam	Orchard grass	Cultivated land with manure	Simulated rainfall (50 mm/h)	Some rainfall events
Dillaha et al. (1989)	4.6 and 9.1	5, 11 and 16	**49 to 93**	−83 to 69	53 to 98	47 to 93	Loam	Grass	Cultivated land	Simulated rainfall	Some rainfall events
Syversen (1995)	5, 10 and 15	7, 14 and 28	**45 to 73**	0 to 88	61 to 91	54 to 91	–	Grass and shrubs	Cultivated land	Natural rainfall	Some rainfall events
Schmitt et al. (1999)	7.5 and 15	6, 7	**48 to 79**	19 to 50	63 to 93	–	Clay-loam	Grass or shrubs or sorghum	Cultivated land with fertilization	Simulated rainfall	Some rainfall events
Patty et al. (1997)	6, 12 and 18	7, 10 and 15	**–**	22 to 89	–	47 to 100 (NO_3)	Loam	Rye grass	Corn	Simulated and natural (650–900 mm/year)	Some rainfall events
Schwer and Clausen (1989)	26	2	**89**	92	95	92	Soil with low permeability	Fescue rye grass, blue grass	Milkhouse waste water	Runoff equivalent to 3 cm/week	2 Years
Uusi-Kämppä et al. (2000)	27 and 97	5 and 10	**−64 to 14**	–	–	–	Clay-loam	Grass	Cultivated land	Natural rainfall	3–7 Years

Total-P is in bold.

successfully over time periods varying from a single event to a year as long as the general conditions of use (size of the buffer relative to sources, maintenance of the grass in reasonable condition, time of year) are appropriate.

The effectiveness of grass buffer strips in reducing the volumes of runoff water varies, according to these studies, from 3% to nearly 100%, with half of the reductions falling between 40 and 100%. The same orders of magnitude are given by Daniels and Gilliam (1996), Patty et al. (1997), or Borin et al. (2005) after a 4-year study. This last author determined that reduction of nutrient loads was driven by the reduction in runoff volumes.

In terms of sediment retention, there is less variability in effectiveness. Retention ranges from 40 to 100%, with more than 50% reduction in more than 95% of the cases. The variability in the percent retention of sediments is closely linked to the experimental conditions and to the factors tested. In most experiments the reduction of the solid load is much greater than that for volume (see for example Borin et al., 2005). The same range of variation is found for particulate-P, with the reduction rate ranging from 50 to 97%. It is never 100% effective under the conditions tested because the clays, which are often heavily loaded with phosphorus, are only weakly retained. Generally, the effectiveness of grass buffer strips with regard to particulate-P and sediments is very similar given their close functional relationship.

The situation is very different for the dissolved forms of P, whose retention percentage varies from −83 to +95, with the most common values being around 20–30%. Although dissolved-P is not dominant form of P in agricultural runoff, these contrasting retention values result in large differences in the retention of total-P (between 8 and 97%). This large range results from the very different dynamics associated with the physical and biological processes governing soluble and particulate species moving in subsurface and surface flows. Variation in hydrologic conditions in different buffer strips may result in a greater contrast in soluble transfers of P including remobilization. The negative values reported indicate that the load of dissolved-P can increase during transfer across the grass buffer strip (Dillaha et al., 1989; Uusi-Kämppä et al., 2000; Trévisan and Dorioz, 2001; Duchemin and Madjoub, 2004).

3.3. Analysis of internal factors controlling the effectiveness of grass buffer strips

Most authors only address internal factors of the buffer, focusing on the width of the grass buffer strip. This reflects the situation that in practice, the size of the strip is the main variable that can be altered through management.

3.3.1. Effect of varying the dimensions of the buffer

Buffer width is often given as the predominant internal factor controlling the efficiency of P and TSS retention. However, some experiments show that the effectiveness of grass buffer strips in reducing sediment losses from fields does not increase linearly with width (Table 2). This suggests that there is an optimum width, beyond which there is little further increase in effect (Castelle et al., 1994; Parsons et al., 1994; Abu-Zreig et al., 2003; Leeds et al., 1994). Kronvang et al. (2000) found that no sediment and particulate-P escaped across a 29 m wide buffer zone. Conversely, it is clear that narrow strips can also be quite effective. Abu-Zreig et al. (2003) obtained a 31% P retention with a grass buffer strip only 2 m wide. Vallières (2005) tested a 1 m wide grass buffer strip and found a substantial retention (60–80%) of total-P and bio-P during medium intensity runoff events. According to Kronvang et al. (2000) 38% of soil and 68% of particulate-P passed through. In addition, these narrow buffer strips can have other beneficial effects, such as stream bank stabilization.

Table 2
Width of grass buffer strips and sediment retention (adapted from Castelle et al., 1994)

Width (m)	Sediment retention (%)
91.5	80
26.2	80
22.4	92
9.1	84
4.6	70

These observations can be explained by considering the mechanism of deposition within the grass strip. Under average conditions of soil texture (silt or sand predominating), most of the sediment transported by the flow is deposited in the first few meters of the grass buffer strip (Schmitt et al., 1999). This initial deposition is associated with a sudden change in the transport capacity at the entrance to the grass buffer strip. The detailed studies of Dillaha et al. (1989) and of Magette et al. (1989) reached the same conclusions, the majority of sediment (53–86% of the input load) is retained in the first 5 m. Further downslope, beyond 5–10 m, the quantities retained are smaller (five to six times less). They are made up of fine particles whose deposition is due to turbulent filtration as described earlier.

The dynamics of particulate-P generally follow those of the sediment. But the granulometric sorting described above must result in a progressive increase in the P content of the sediments down gradient from the top of the buffer, setting an upper limit to the retention of particulate-P. Consequently, Syversen (1995) considers the optimum width to be in the range of 5–12 m for any grass buffer strip. According to Schmitt et al. (1999) the percentage retention of bio-available P is always less than that of total-P and is only significant (>60%) in the case of buffers that are sufficiently wide (>15 m) to influence the transfer of the fine and dissolved fractions, which closely constitute the pool of bio-available P.

In principle, the transfer of dissolved forms should be even more sensitive to the width of the filtering system because of the phenomena involved. Infiltration and storage in the soil requires a greater distance over which to develop. Thus, a doubling of the width of the grass buffer strip, for example from 7.5 to 15 m, does not significantly improve the retention of sediment, but causes a clear drop in the concentrations and flux of all the dissolved contaminants studied, including P (Schmitt et al., 1999). However, not all the studies confirm this result. The data are very variable and increases in dissolved-P concentrations have been observed during certain events (Table 1). Despite that, for most slopes with less than a 10% grade, a strip of 8–15 m was sufficiently effective (giving a P retention of 60%).

Some authors prefer to consider the ratio of the area of buffer strip to that of the runoff area (source zone) as the relevant independent variable. In our opinion this approach is best suited to a common field condition where a topographic convergence concentrates water flow towards a particular edge of the fields. Thus ratio of buffer area/source zone is a critical factor influencing the ability of the grass buffer strip to function under potentially very high loads or concentrated runoff. In the work of Leeds et al. (1994), these ratios are quite low, varying from 0.1 to 0.3. In studies by Doyle et al. (1977), a ratio of 0.5 resulted in the retention of dissolved-P of about 60%, whereas it reached barely 10% for a ratio of 0.2. In another review, Patty et al. (1997) noted a range of recommendations by the authors extending from 0.02 to 0.7, and also observed a tendency for higher retention as the ratio increases. Thus high values for this ratio seem particularly critical where a topographic concentration of runoff is likely.

Whatever method is used to express the dimensional factor for buffers, there is high variability in the experimental results reported in the literature (e.g., Table 2). Consequently, it is difficult to formulate definitive recommendations to farmers, as illustrated by the doubling of standard sizes recommended by the Soil Conservation Service of the USA (now NRCS, Table 3) from 1988 to 1990, and then again from 1990 to 1997. Of course, these recommendation were also sensitive to a changing perception of the acceptability of the grass buffer strips to farmers and reflect that change as well.

3.3.2. *Effect of the vegetation*

The ability of grass buffer strips to reduce total-P transfer to surface waters is also affected by the nature of the roughness created by the plants. The increase in plant cover (ratio of the area covered by vegetation to that of total buffer area) reduces the speed of runoff and thus the energy available for the transport of particles (Bishnoi, 1991; Pearce et al., 1997) and limits the erosion of the buffer strip itself (Evans, 1990 cited by Chambers et al., 2000). This results in increased retention of the particles and their attendant P load. According to the laboratory experiments of Rogers and Schumm (1991): (1) a plant cover of at least 40% is needed to obtain a significant retention (80%) of the load of sediment and (2) retention reaches a threshold beyond 60–70% cover.

The height of the vegetation is another parameter that has been the subject of several experiments. Cole et al. (1997) observed that an increase in the height of the vegetation does not noticeably improve the functioning of the grass buffer strip. Pearce et al. (1997) even affirm the converse: close-cut vegetation is preferable because it does not fall over under the influence of rain or runoff. Lodging of the grass creates preferential routes for runoff, which then reduces the ability of suspended matter to be retained on plant surfaces.

The phenology of the plants in the grass strip sometimes appears to be of importance because it results in a variable relationship between plant dynamics (growth, tillering, etc.) and the occurrence of erosive rainfall. In Ohio, Leeds et al. (1994) recommend cool season plants rather than warm season plants to obtain maximum cover during the rainy season.

Furthermore, there are indirect effects of the grass on P retention via its action on the soil (Table 4). Briefly, Schmitt et al. (1999) report that the maximum effect (>60% of retention), for bio-P, sediment (TSS), total-P, or dissolved-P, is obtained with perennial, herbaceous vegetation. Other forms, such as mixtures of herbs, trees and bushes, or young grassland, are less effective. The differences observed are linked to the increase in permeability obtained by the long-term effect of grass on soil structure (Monnier, 1965). However, one should note that for equal strip width, the type of vegetation yields gains of at most 20%, suggesting that this variable is not a key factor. This may explain why, in many circumstances, the vegetation effect cannot be demonstrated in situ (Uusi-Kämppä et al., 2000). Schmitt et al. (1999) found that woody plants in the lower half of the grass buffer strip do not improve the performance of the system. However, this result cannot be generalized: comparisons of woody and herbaceous vegetation have yielded contradictory results. Certain studies show no clear differences in the retention of sediments or nutrients

Table 3
Evolution of Soil Conservation Service (SCS) recommendations for the width of grass buffer strips

Standards 1988 (SCS, 1988)		Standards 1990 (SCS, 1990)		Standards 1997 (SCS, 1997)	
Slope (%)	Minimum width (m)	Slope (%)	Minimum width (m)	Slope (%)	Minimum width (m)
<1	3	0–5	6	0.5–5	11–22
0–10	5	5–6	9	≥5	36–71
		6–9	12		
10–20	6	9–13	15		

Table 4
Effect of vegetation type (species, age) and width on retention efficiency of grass buffer strips (adapted from Schmitt et al., 1999)

Length (m)	TSS (%)	Total-P (%)	Bio-P (%)	Dissolved-P (%)
Sorghum				
7.5	63	48	39	31
15	65	51	46	50
Grass (2 years old)				
7.5	89	71	53	29
15	87	70	54	30
Grass + tree saplings (2 years old)				
7.5	79	57	42	19
15	88	71	56	35
Grass meadow (25 years old)				
7.5	89	71	53	29
15	93	79	65	43

(Daniels and Gilliam, 1996; Syversen, 1995), while others show an advantage to herbaceous vegetation (Cooper et al., 1986; Parsons et al., 1994). However, Michaud (personal communication) notes that trees and shrubs are more stable over the long-term and connote a more sustainable landscape.

3.3.3. Effect of soil texture and structure

Given the role of infiltration on the retention of total-P, factors controlling the permeability of the soil are important in enhancing the retention effectiveness of the grass buffer strip. As noted above, vegetation has a clear role in establishing structure leading to higher permeability. In addition, the structural state of the soil surface also deserves particular attention. According to work by Cooper et al. (1995) in riparian zones, the degradation of soil structure following compaction by grazing results in a decrease in buffer effectiveness.

Texture has an equivalent role. Schwer and Clausen (1989) found a large difference in retention of total-P and dissolved-P between two grass buffer strips, one established on a sandy soil (retention 92 and 98%, respectively) and the other on a silty clay (33 and 12%). A higher retention capacity on sandy soils was also noted by Magette et al. (1989). Consequently, it would be logical to modify the recommendations for buffer strip width as a function of soil permeability (Uusi-Kämppä et al., 2000).

3.4. Analysis of external factors controlling input of runoff

When the input of runoff exceeds the capacity of the buffer, the retention effectiveness for phosphorus and sediments declines because of saturation of the soil within the buffer and lower residence times during the transport process. The decrease of retention can be dramatic. In the experimental system of Schwer and Clausen (1989), the retention of total-P fell seven-fold when the input flow increased five-fold. In the work of Pearce et al. (1997), the effect of the grass buffer strip on the flow became negligible when the depth of the water layer exceeded that of the vegetation, which often happens during periods when snow is melting (Schellinger and Clausen, 1992).

Exceeding the buffer's capacity to retain water is common with concentrated flows. The parts of the grass buffer strip that receive the concentrated flows are quickly saturated, and thus the overall effectiveness of the buffer falls noticeably (Dillaha et al., 1986b, 1989). In fact most authors who tackle this question consider the nature of the flow (concentrated or diffuse) to be a key factor in the effectiveness of the buffer (Blanco-Canqui et al., 2004). This belief results largely from field observations. Studies of P retention under condition of concentrated flow are rare, whereas topographical situations (e.g., natural or artificial depressions) and practices (tractor wheels, grazing) are common in the field and encourage this type of flow (Trévisan and Dorioz, 2001).

4. Temporal effects on P dynamics

4.1. Temporary declines in buffer effectiveness due to soil saturation and silt deposition

Grass buffer strips are often calibrated under average meteorological conditions. Extreme situations may result in submersion by water or by sediment, which leads to a drop in their turbulent filtration and infiltration properties. Repeated rain events produce similar effects, being accompanied by a progressive diminution in the retention of sediment as it accumulates (Dillaha et al., 1986a). Uusi-Kämppä et al. (2000) found that accumulation of sediment could lead to the release of dissolved-P during subsequent runoff periods. In general, these changes constitute only a temporary degradation of system function. After the flood, the water evaporates or infiltrates and the vegetation is capable of regrowing through most of the sediment deposits. This consolidates the new sediment deposits and thus restores stability and the retention capacity of the system (Parmeland, 1995). This return to the initial state requires a few weeks and favourable growing conditions.

4.2. Seasonal effects on the input–output balance

Several factors that control the functioning of the grass buffer strip vary with the season, notably the characteristics of the input flow. In addition, the time of year may influence the actual functioning of the retention mechanisms thus altering the balance between retention and export. As a fundamental driver, temperature controls the intensity of biological phenomena and thus the capacity of the grass strip to immobilise the retained total-P. The accumulation of plant residues in the dormant period leads to periodic exports of dissolved-P, partly originating from the stored total-P, during winter storm events or snow melt (Turtola and Jaakkola, 1995; Uusi-Kämppä et al., 1997; Yli-Halla et al., 1995). In a similar fashion, P mobility increases during seasonal flooding of grass buffer strips.

All these seasonal processes: (1) give the operation of the grass buffer strip a cyclical character whose magnitude depends on the climate and the year (Syversen, 1995) and (2) result in a time lag (in quantity and composition) between inputs and outputs. The true effectiveness of the grass buffer strip can therefore only be evaluated over the long term.

4.3. Long-term loss of effectiveness due to sediment accumulation and phosphorus saturation

In the long term, the restoration of favourable surface conditions by means of plant growth may become impossible because of the continued accumulation of sediment. Changes in the microtopography and permeability then create conditions favouring internal erosion of the grass buffer strip (Dillaha and Inamdar, 1997). Such a process would probably take several years. The compaction of the soil surface by machinery or animals leads to similar symptoms, but at a more rapid rate. The long-term accumulation of total-P could also, in theory, saturate the system with P to create conditions favourable for the release of dissolved forms from the soil of the grass buffer strip (Muscutt et al., 1993). The top 2–3 cm of soil within the grass buffer strip receives a disproportionately large amount of total-P, and thus must play a dominant role in this process.

All things considered, one might hypothesize that, beyond a certain threshold (not yet established), (1) the retention of incoming total P cannot be sustained, and (2) the quantity of dissolved-P released from previously stored P increases.

5. Discussion and conclusions

The temporal and spatial dynamics of the P in the runoff moving across the grass buffer strip and the effectiveness of the retention of this P, is the result of a chain of physicochemical and biological processes, which interact in a hierarchical fashion, and which are triggered by the local changes in flow conditions due to the hydrological properties of the buffer.

The processes involved follow one another in time. The rapid physical or chemical processes occur during the runoff phase with rates varying according to the type and intensity of rainfall and the season of occurrence. These processes are spatially differentiated from the top to the bottom of the buffer strip due to the gradient in velocity of the runoff. The initial storage of total-P occurs during this rapid runoff phase. Both the permanence of this initial storage and the maintenance of the P storage capacities for future events is predominantly linked to slower and more long-term processes that are mainly biological in origin. These processes result in (1) a return to a favourable physical state of the system that enhances capture of dissolved-P (e.g., restoring high soil permeability via fine root development, renewing the capacity of the soil to capture water via transpiration) and particulate-P (e.g., consolidating sediment deposits and maintaining vegetative roughness) between runoff events and from one season to another, and (2) the incorporation of P into the cycle of the soil–vegetation system with seasonal fixation in biomass, litter fall accumulating organic-P in detritus, and the periodic release of P through decomposition. Additional studies are needed to understand the capacity of soils to retain dissolved-P through fixation (sorption–precipitation processes) and the variables that influence this capacity (e.g., soil type, pH, organic matter).

This spatial and temporal differentiation of the functioning of the grass buffer strip determines both the (1) seasonal dynamics and the overall mass balance of P input and output, and (2) effectiveness of the buffer system to retain the different forms of P (with their differential impacts on downstream ecosystems). These two aspects provide an integrative measure of the role in of grass buffer strips in agricultural management. However, a more comprehensive understanding of the diversity of processes governing P dynamics in grass buffer strips, as described above, may be vital to the future development of more accurate models of buffer functioning and better use of this knowledge in creating sustainable agricultural systems in the landscape.

5.1. Towards a dynamic model of the functioning of the grass buffer strip

Deterministic models of grass buffers strips have focused on the infiltration of water and the accumulation of sediment as the major mechanisms of P retention, and on the release of P by erosion and leaching from the soil. In this approach, buffer function is viewed as the balance of opposing short-term fluxes controlling P dynamics (Lee et al., 1989). Simplified in this way, the functioning of the grass buffer strip can be simulated on the time scale of a rainfall event. In our review, few studies lasted for more than one season, and the data used for parameterization are typically representative of single events. However, the functioning of the grass buffer strip does not cease between runoff events, and there are a set of complex processes and feedbacks among the sediment, phosphorus, and the plant–soil system that occur on seasonal and annual time scales. We therefore propose a conceptual model that includes the spatial and temporal dynamics of P in the context of the environmental reactivity of the various forms of P (Fig. 3).

5.1.1. Reduction in the flows of P transferred during a runoff event

Hydrology is the primary factor controlling the P dynamics within a grass buffer strip. Infiltration and the reduction in velocity of the inflow water as it moves through

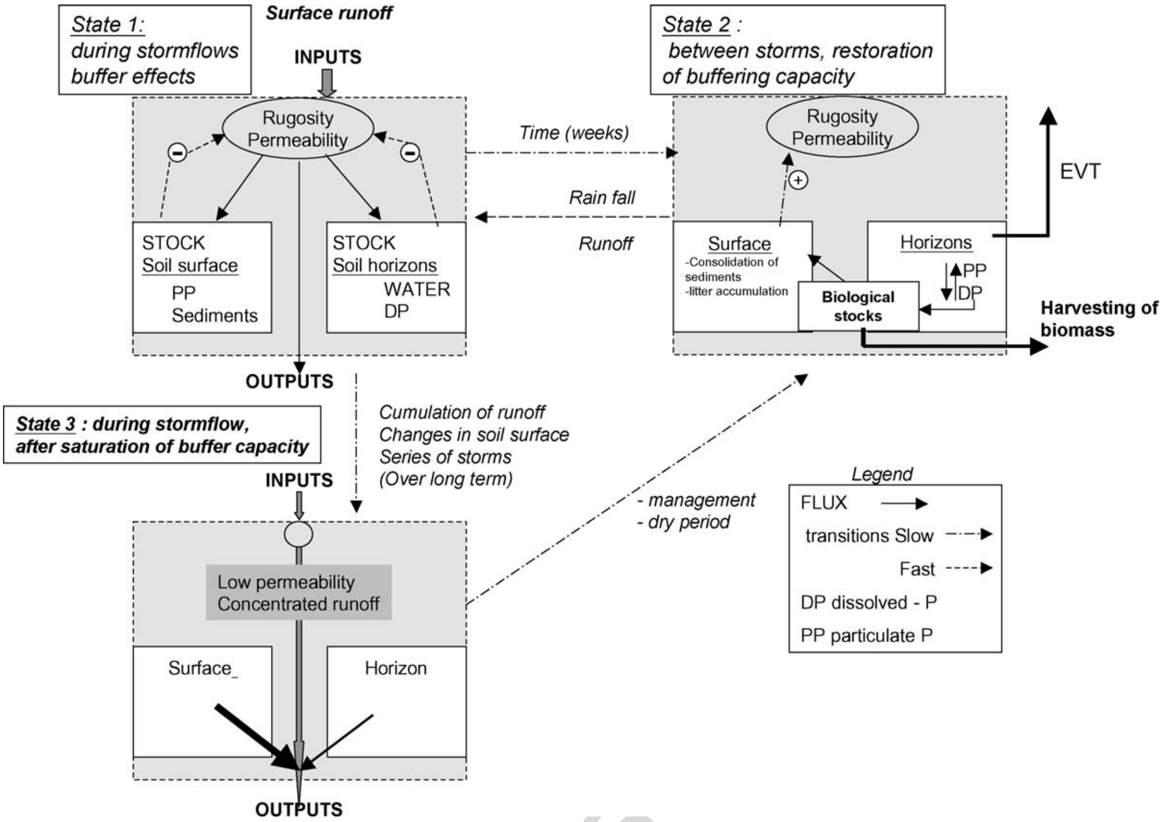

Fig. 3. Conceptual diagram of spatial and temporal P dynamics in an evolving grass buffer strip.

rougher medium created by vegetation result in a reduction in the capacity to transport solids over the extent of the buffer strip (Munos-Carpena et al., 1999). This can be observed at interface between the runoff zone and the buffer zone by deposits of coarse fractions. Further down, the presence of a dense plant cover induces a turbulent filtration phenomenon that is effective in removing some of the finest fractions of suspended sediment. This combination of deposition and filtration results in a selective transfer of the particulate-P with the highest reactivity at the bottom of the buffer. This can partially reduce in the positive benefits of the buffer, as the most reactive (and bio-available) particulate-P is now closest to the point of entry to surface waters.

The processes of deposition and filtration take place at the soil surface, and thus have little effect on the other bio-available fraction, namely dissolved-P. With these processes the contact time between the soil surface and the runoff is too short for major biochemical processes affecting dissolved-P. The fate of the load of dissolved-P depends primarily on infiltration. Infiltrated water disperses within the soil pores, transferring the dissolved-P into the soil mass. Once this P is in the soil, the potential for later reactions remain, such as absorption by plants, adsorption onto the soil, or chemical precipitation. The intensity of these soil–phosphorus interactions depends on soil properties (texture, pH, etc.) and on its P content.

The accumulation of water and sediments determines the potential for short-term negative feedbacks from the buffering process itself. This can occur during the rainfall event itself or in the period between events. For example, the deposition of particles at the soil surface tends to alter the flow conditions and thus increase the erodibility of the soil. In addition, the increase in the water content of the soil modifies its permeability and thus reduces the soils ability to store additional dissolved-P.

5.1.2. Restoration of buffering properties between floods

Colonization of this buffer zone by vegetation contributes to stabilization of the stored particles and associated particulate-P, reducing the erodibility of the deposits and maintaining the permeability of the soil surface. When the weather is favourable, evapotranspiration also restores the infiltration capacity and thus soluble-P adsorption within the grass buffer strip.

5.1.3. Biological recycling and seasonal dynamics

All the forms of stored P can contribute to plant or microbial nutrition. Transformed into organic-P, phosphorus is partially returned in the form of litter, which enriches the soil surface with labile forms of P and constitutes a favourable state for the seasonal release of dissolved-P or of fine particles very rich in P (Frossard et al., 1989; Sharpley et al., 1992; Toora et al., 2003). This release can be limited by harvesting the biomass produced in the buffer. This results in a modification of the timing and the form of export of part of the P. The relationship between P removal in biomass and P emission from the buffer is not well documented, and thus the environmental impacts of possible harvesting practices require further study.

5.1.4. Long-term dynamics

Over a period of many years, grass buffer strips could become a source of P to adjacent surface waters. The accumulation of sediments leads to physical changes tending to render the grass buffer strip ineffective. This physical degradation might be corrected by lightly tilling the soil. Similarly, the accumulation of particulate-P could, in theory, lead to the saturation of the P fixation capacity of the thin surface layer of the soil where the runoff occurs. Such a change would increase the risk of release of the dissolved-P. However, in the current literature, no negative feedback from the accumulated concentration of total-P in soils has been observed in the field. The increase of stored total-P seems to have a negligible effect on subsequent sorption or precipitation of P.

5.2. Dynamics of multiple pollutants in the grass buffer strip

The grass buffer strip simultaneously alters the transfer of all the compounds transported by water over its surface or through the soil. In the initial stage of the buffering process, the constituents of diffuse pollution disperse according to their physico-chemical properties (including simple storage in soil water, adhesion, adsorption, complexing, precipitation, chemical reaction, etc., see Patty et al., 1997; Coyne et al., 1998) and the hydraulic conditions within the grass buffer strip. For those soils that are sufficiently permeable, the dynamics of dispersion that occur within the soil helps to modify substances in solution like herbicides, pesticides, etc. On the soil surface, other retention dynamics affect particulate forms containing pollutants like metals (e.g., as Cd, Zn, and Cu) and biological agents such as bacteria and viruses (Schmitt et al., 1999; Schmidt, 2003).

The next step in the buffering process, which takes place over a longer time frame, again depends largely on the properties of the substances: (a) more or less complete biodecomposition and re-emission for organic molecules, (b) passage into the gaseous phase for nitrogen leading to a long-term, sustainable buffering effect, or (c) simple accumulation within the soil–plant system, which is the case for P or metallic elements, with the risk of release and/or toxicity at some future time.

During storage, the retained substances may interact with each other with synergistic or antagonistic effects. These potential interactions are not well documented. One might, for example, envisage that the decomposition of organic molecules would be stimulated by additions of P or N. This could result in, on the one hand, increased decomposition of undesirable compounds such as insecticides, or, on the other hand, liberation of nutrients or trapped residues such as herbicides. P release has been observed in wetlands receiving excessive amount of nitrate from cultivated fields (Paludan, 1995). Thus, the accumulation of diverse pollutants and/or nutrients within the same storage locations in the buffer is not necessarily positive in environmental terms.

The optimal requirements for retention and storage differ according to the nature of the pollutant and its behaviour. For example, an optimum situation for P is not necessarily the same as for N or herbicides. The initial retention of sediments and their load of pollutants occurs within the surface layer of soil. This compartment may be easily saturated (e.g., with P) and can be very sensitive to displacement of stored pollutants during runoff events. Thus, the potential retention capacity decreases drastically as typical runoff flows, and especially concentrated flows, increase from one site to another (Preedy et al., 2001). Therefore, in order to optimize the effectiveness of buffer function within the context of a grass buffer strip of reasonable dimensions, the strips should be dispersed and placed immediately below the fields that emit surface runoff. This avoids the build-up of concentrated runoff and spreads the potential for saturation among more sites.

The situation is different if the objective is to buffer pollutants or nutrients that are in a dissolved or degradable form, or are capable of being denitrified. The aqueous transfer pathways are somewhat different, the effect develops within the soil mass, and the residence time becomes the limiting factor. Placing strips to buffer dissolved pollutants in low spots or along river banks is therefore fully justified. However, these sites are less optimal for P retention as there is a higher likelihood of temporary anoxic conditions and the subsequent reductive dissolution of particulate-P during these seasonal pulses.

The diversity and interactivity of the dynamics described above illustrate the difficulties that will arise when establishing grass buffer strips that are both effective and multi-functional, while being attractive and biologically diverse as suggested by current agricultural and environmental policies.

5.3. Using grass buffers strips despite their limitations

In light of the literature reviewed, we feel that grass buffer strips have a role in controlling diffuse phosphorus pollution, but that this role is both specific to place and limited in duration.

Studies agree that grass buffer strips are a practical way of managing agricultural fields. Over a period of years, they can significantly reduce (by at least half) the flows of sediment and particulate-P transferred by diffuse runoff, without requiring unreasonable practices, large amounts of space, or specialized maintenance. The P reductions are not always large, because the buffer effect can be limited and dissolved forms of P and bio-available P can be remobilized in winter. In addition, the buffer effect can also be rather small where concentrated runoff occurs, which often occurs under French conditions. However, it is important to note that grass buffer strips alongside ditches also provide a completely different function by protecting the banks from erosion (Duchemin and Madjoub, 2004).

The generalizations that we have drawn from the literature seem particularly applicable to temperate French and European agriculture. The small-sized fields, the high density of drainage ditches, the lack of high intensity rainfall events, and the diversity of agricultural uses are conducive to the application of the buffer strip. However, in northwestern France, erosion of silt soils may results in muddy runoff events characterized by very high TSS concentrations (sometimes reaching 60 g l^{-1} according to Angéliaume and Wicherek, 2002), which can lead to significant property damage (Boardman et al., 2003). In such conditions, the grass filter strip might be ineffective.

The decision to establish grass buffer strips in a given region of France should also include other considerations, e.g., the environmental context, the soil type, the background levels of pollutants, the feasibility of establishment within the local farming system, the role of buffers in improving the public image of agriculture, and the possibilities for financial compensation, notably via the new Common Agricultural Policy (CAP) arrangements. However, socio-economic considerations can often be more influential than scientific ones. Thus, the possibility of converting obligatory "set-asides" into "grass strips" placed along watercourses may focus future recommendations towards these locations. Placement of buffers adjacent to a watercourse, which was devised as a solution to the nitrate problem, unfortunately is not ideal for P retention, which requires control further uphill in proximity to the agricultural fields. Nevertheless, if the regional and socio-economic situation is favourable, the detailed decisions about placement and design of buffers will be made on the basis of other parameters such as slope, soil type, state of P in the soil, etc. The challenge is to find the conditions in which the grass buffer strip functions optimally.

The consensus from the literature suggests that this optimum corresponds to the following conditions:

1. The incoming flow is due exclusively to diffuse runoff, which sets a limit on the mean incoming flow and thus also on the size of the source area. Working within this limit can permit the optimal placement of the buffer, and when implemented in conjunction with certain soil tillage practices at the grass buffer strip/crop interface, maximizes the retention effectiveness of the buffer.
2. The dimensions (width, length, shape, total area) of the grass buffer strip are established with respect to the uphill/source environment (slope, erosion risk, etc.) and the downstream/sink environment (levels of contamination, sensitivity of local receiving watercourses). It is difficult to arrive at specific values from the literature, but it seems that 5 m is a fairly general minimum width for slopes from 1 to 10%, with the range being 5–10 m.
3. The vegetation should be first and foremost well rooted, with a dense cover, and maintained like a lawn by regular mowing (two to three times per year under our climatic conditions) with the cuttings removed. The choice of species seems to be of secondary importance.

Some of these conditions may vary over the course of the year, and as a consequence, the retention effectiveness of the grass buffer strip varies. Retention is minimal at the time of very heavy flow (snow melt or exceptional rainfall which inundates the strip) and at times when the vegetation is growing slowly. The value of grass buffer strips in the control of P transfers thus depends on the frequency of these events and the overlap of the timing of potential runoff and the retention capacity of the functional elements within the grass buffer strip.

In summary, the knowledge needed to design effective grass buffer strips is currently available, but only by using a rather unrepresentative portion of the literature. This is particularly true for French farming systems with their diversity of field layouts. Experimental evidence detailing the dynamics of the buffer system is generally lacking, so decisions about design and implementation depend largely on the use of plausible hypotheses and practical expertise. The greatest uncertainties are relative to (1) the ability of grass buffer strips to store P over the long term, and (2) the resistance of these buffers to extreme events such as major storms or "muddy runoff." Furthermore, the agronomic/economic balance between undesirable effects (introduction of weeds, pests, etc.) and positive benefits (reduction in P emission, aesthetics, etc.) has not been clearly established. The likely proliferation of grass buffer strips throughout much of the cultivated landscape means that work on guidelines is urgently needed.

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