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Impacts of anthropic pressures on soil phosphorus availability, concentration, and phosphorus forms in sediments in a Southern Brazilian watershed

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Abstract

Purpose The transfer of soil sediments and phosphorus from terrestrial to aquatic systems is a common process in agricultural lands. The aims of this paper are to quantify the soil phosphorus availability and to characterize phosphorus forms in soil sediments as contaminant agents of waters as a function of anthropic pressures.

Materials and methods On three subwatersheds with different anthropic pressure, water and sediment samples were collected automatically in upstream and downstream discharge points in six rainfall events during the tobacco growing season. Phosphorus desorption capacity from soil sediments was estimated by successive extractions with anion exchange resins. First-order kinetic models were adjusted to desorption curves for estimating potentially bioavailable particulate phosphorus, desorption rate constant, and bioavailable particulate phosphorus.

Results and discussion The amount of bioavailable particulate phosphorus was directly correlated with the iron oxide content. The value of desorption rate constant was directly related with the total organic carbon and inversely with the iron oxide contents. Phosphate ions were released to solution, on average, twice as rapidly from sediments collected in subwatersheds with low anthropic activity than from those ones of highly anthropic subwatersheds. Anthropic pressure on watershed can engender high sediment discharge, but these solid particles seem to present low phosphorus-releasing capacity to water during transport due to the evidenced high affinity between phosphorus and iron oxide from sediments.

Conclusions Anthropic pressure was related with sediment concentration and phosphorus release to aquatic systems. While natural vegetation along streams plays a role on soil and water depuration, it is unable to eliminate the phosphorus inputs intrinsic to the agricultural-intensive systems.

Recommendations and perspectives The contamination of water in watershed by phosphates is facilitated by the erosion process and the traditional tobacco cropping system. Urgent measures for erosion control must be adopted, in accordance to conformations of landscape and the local inhabitants' needs. Among them, those worth pointing out are the adoption of a conservation crop system, regeneration of riparian zone, and reduction of the phosphate doses added to soil for tobacco cultivation.

Keywords Anthropic activity · Nutrient cycling · Pollution · Sediment · Soil erosion · Water quality

1 Background, aim, and scope

In the southern region of Brazil, the anthropic activity and its consequences on water quality of sloping land watersheds have not been well studied. This region includes

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approximately 400,000 small farms, each one with an average area of 10 ha. The Poverty Combat and Environmental Recuperation Program of the State of Rio Grande do Sul (RS-Rural) was initiated in 1999 to alleviate the impoverishment which affects 70% of the farms located in this state and aims to propose alternatives to soil use and management for increasing yield production and improving environmental quality, especially of water. A preliminary study showed high losses of sediments, nutrients, and pesticides due to great rainfall intensity, the steep slopes, and the tobacco crop management system (Rheinheimer et al. 2003c; Gonçalves et al. 2005; Bortoluzzi et al. 2006). It is worth noting here that in watersheds with a low anthropic activity, i.e., with a small proportion of cultivated soils and adequate watershed planning in a forest context, the observed contamination of the sediments is in general lower than those of high-human-activity areas.

As shown in the literature, P outputs in streams depend on soil type along with management and transport processes (Omernik 1977; McDowell et al. 2001b; Reynolds and Davies 2001). P can be transported in soluble or particulate form (adsorbed on inorganic colloids or as component of organic substances), and its transfers can vary in time and space (Sharpley et al. 1992, 1995; Dils and Heathwaite 1996; Correll 1998; Leinweber et al. 1999; Reynolds and Davies 2001).

In the watershed discharges, the available *P* values are generally lower under forest covers than in agricultural areas (Omernik 1977). However, amounts of total and soluble P forms do not appear to be reliable indicators of the eutrophic state of water since the soil sediment can have different desorption capacities (Correll 1998). In contrast, the rate between particulate bioavailable P (α) and total particulate P [P (α)/Pt×100] allows the assessment of phosphorus contamination (Sharpley et al. 1992). This rate may vary from 9% to 69% for areas under conventional cultivation and natural pasture, respectively. The orthophosphate can be adsorbed to colloid surfaces with different energy degrees (Parfitt 1989) and can be released to water at different rates, depending on its bonding energy (Barrow 1983; Rheinheimer et al. 2003a; Siemens et al. 2004).

Dissolved inorganic P is readily available for algal absorption, causing water eutrophication process (Sharpley et al. 1992). Despite the various studies carried out to determine the bioavailable P in soil sediments (Sharpley 1985; Sharpley et al. 1992; Dils and Heathwaite 1996; McDowell et al. 2001a, b), few of them have used a kinetic model to obtain the maximum P desorption (buffering capacity) and the desorption kinetics constant (Koski-Vähälä and Hartikainen 2001), the kinetic parameters that characterize the magnitude and the fate of P in aquatic systems.

The small particles (i.e., <2 μm) and some clay mineral species are selectively eroded during runoff, containing high P concentrations with high potential desorption capacity (Sharpley 1985; Bortoluzzi 2004). Therefore, information on kinetics is invaluable for assessing the magnitude of the pollution in space and time, along with successive extractions with anion exchange resin (AER) to characterize P availability in soil sediments (McKean and Warren 1996; Rheinheimer et al. 2003b). Having this into account, it is easy to realize that the knowledge of the total amount of soluble or total P does not suffice to ensure a full understanding of an environmental impact.

The aims of this paper are to quantify the soil phosphorus availability and to characterize phosphorus forms in soil sediments, contaminant agents of waters, as a function of anthropic pressures. To achieve this purpose, a comparison was made among three landscape conformations presenting different anthropic activities in partly transformed forest ecosystems as well as more intense agricultural areas, especially those cultivated with tobacco.

2 Materials and methods

2.1 Site description

The Lino stream watershed is located in the Nova Boêmia community, town of Agudo, Rio Grande do Sul state, Brazil, at coordinates Universal Transversal Mercator (UTM) 22 J 280000–283500 m/6733500–6737000 m (Fig. 1). This typical agricultural watershed is an important tributary of the Jacuí River. With 480 ha, it is one of the four reference watersheds of the Environmental Monitoring Program, implemented by the RS-Rural (Rheinheimer 2003). As concerning the geological aspects, the watershed belongs to the "Serra Geral Formation," which presents basaltic hillsides and localized outcrops of Botucatu sandstone. The land altitudes range from 100 to 500 m with long pendants and short slopes normally greater than 25°. The soils are classified as Mollisols and Inceptisols (Soil Survey Staff 1999) and the vegetation is composed by remnant seasonally deciduous forests in different stages of succession. The climate is humid subtropical, with an average annual rainfall of 1,600 mm and an average annual temperature of 19°C. Almost 25% of the watershed's area is occupied by annual crops and more than 60% by native forest cover. Approximately 90% of the 36 farm production units are devoted to tobacco production, which needs high agricultural inputs, especially chemical fertilizer containing N, P, K, and S. The addition of fertilizers is still performed in a precautionary system, in kilogram per hectare per year: N=180, P_2O_5=130, K_2O=250, and SO_4=60. Tobacco is an intensively tilled crop, and its production system typically includes two to six cultivation operations per year (disk plow and disk harrowing 0.20 m soil disturbance depth). In addition to intensive tillage for weed control and preparation for tobacco transplanting, tobacco production employs many pesticides (insecticides, fungicides, and herbicides) to enhance leaf growth.

Topographic map, aerial photographs, and field work using a navigation GPS device were used to define the water divides, drainage system, roads, and diffuse and punctual pollution sources (see Fig. 1 and Table 1). In general, the roads encompass 3.3% to 4.1% of the total area of the watershed, and the farm buildings are located close to watercourses, originating punctual pollution sources due to bovine, pig, and chicken production units (Bigarella 2003; see Table 1 and Fig. 1). The different land uses were grouped together in annual crops, forest cover (native forests and reforestation), perennial pasture, and other uses (fields cultivated for subsistence, orchards, installations, and roads). A georeferencing information system, including the points of sediment sampling, was created with ArcView® 3.2 program, allowing us to localize in a map (see Fig. 1) the following selected areas for study:

- Subwatershed A, with a landscape conformation based on high sloped relief and high human activities. Agricultural fields closed to streams and no protection by vegetation in stream-adjacent areas. In this subwatershed, A1 (upstream: UTM 22 J 282475; 6734637) and A2 (downstream: UTM 22 J 282259; 6735016) points were sampled
- Subwatershed B, with a landscape conformation based on high sloped relief and low human activities. Upstream point (B1: UTM 22 J 282926; 6735668), which has preserved native vegetation along the streams and downstream one (B2: UTM 22 J 282666; 6735506), presenting few agricultural fields
- Subwatershed C, with a landscape conformation based on high sloped relief and high human activities. However, this subwatershed presented high soil cover by natural vegetation around stream areas; therefore, the agricultural fields are far from streams in both points C1 (upstream: UTM 22 J 281670; 6735908) and C2 (downstream: UTM 22 J 281732; 6735728)

Water and suspended sediments were collected at the exit of six points (subwatersheds A, B, and C—upstream and downstream; see Fig. 1). Water and sediment samples were taken immediately after each of six rainfall events during tobacco growing season, in October 01, 2003 (23 mm), October 08, 2003 (16 mm), October 25, 2003 (61 mm), December 12, 2003 (27 mm), December 15, 2003 (83 mm), and February 01, 2004 (34 mm). The employed samplers are an adaptation of the model US U-59 (CEW-EH-Y 1995), installed in pairs in the streambed of the watercourse. The suspended sediments of the two automatic samplers were mixed in a single sample. Then, the samples were maintained at 4°C and transported to the Soil Chemistry and Fertility Laboratory of the Federal University of Santa Maria, Brazil.

In 2002, soil samples were collected from the 0–0.05 m layer at 42 points chosen in order to represent the spatial variability of soil uses, including areas with annual crops, natural pastures, native forests, and reforestation. To collect

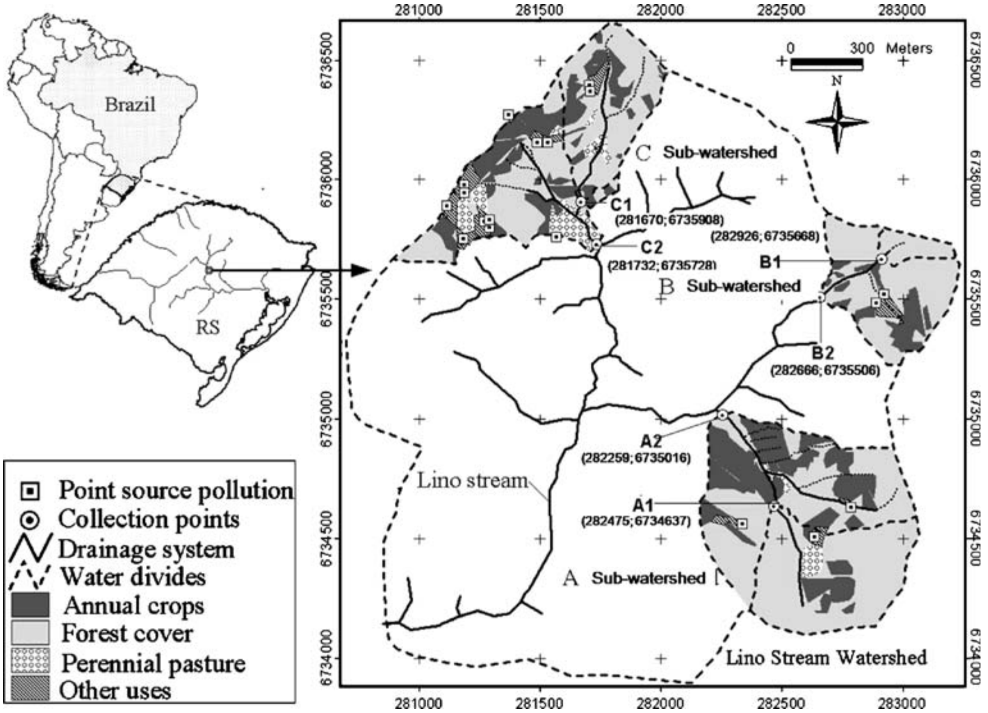

Fig. 1 Point source pollution, collection points, drainage system, water divides, and land use (annual cultures, forest cover, perennial pasture, and other uses) in the three subwatersheds (*A*, *B*, and *C*) monitored in Lino watershed, Agudo, RS, Brazil

Table 1 Areas and relative contribution of the land uses in each collection point of the three subwatersheds monitored in Lino watershed, Agudo, RS, Brazil

Subwatershed	Collect point	Total	Annual crops	Permanent forest, ha (%)	Perennial pasture	Other uses[a]
A	A1	26.9	3.2 (11.9)[b]	21.4 (79.5)	1.0 (3.7)	1.3 (4.8)
	A2	69.2	17.1 (24.7)	48.1 (69.7)	1.6 (2.3)	2.4 (3.5)
B	B1	3.1	0.0 (0.0)	3.1 (100)	0.0 (0.0)	0.0 (0.0)
	B2	24.3	3.9 (16.0)	18.5 (76.1)	0.4 (1.6)	1.5 (6.2)
C	C1	21.2	4.2 (19.8)	16.0 (75.5)	0.7 (3.3)	0.3 (1.4)
	C2	48.3	12.0 (24.8)	29.5 (61.1)	4.6 (9.5)	2.2 (4.5)

[a] Subsistence cultivation, orchards, gardens, installations, and roads

[b] The dates between parentheses are in percent

the soil samples, four trenches (0.20×0.20 m—wide × thickness) were opened in each of the points randomly chosen inside each area. These four subsamples were mixed, air-dried, sieved (<1 mm), and stored at room temperature. The rates of available phosphorus (Mehlich I) were grouped in five levels of availability (CQFS-RS/SC 2004): very low (0–7 mg kg^{-1}), low (7.1–14 mg kg^{-1}), intermediary (14.1–21 mg kg^{-1}), high (21.1–42 mg kg^{-1}), and very high (42.1–69.5 mg kg^{-1}). To build the map, the Software ArcView 3.2® with the Spatial Analyst extension® version 1.1 was used. The method of triangulated irregular network was employed for interpolation of available phosphorus rate georeferenced punctual values, distributed in five levels on the watershed geographic map, employing the tool “surface-interpolate grid.”

2.2 Analytical methods

In laboratory, initial pH values were determined in water and sediment suspension samples. Then, an aliquot of each sample was filtered in a 0.45-μm-diameter porous membrane. On the filtered solution, soluble P was determined following the Murphy and Riley (1962) method. After evaporation at 100°C, the sediment concentration was quantified. Iron was extracted by dithionite–citrate–sodium bicarbonate (Fed; Mehra and Jackson 1960) and total organic carbon (Tedesco et al. 1995). P of sediment was extracted by acid digestion (H_2O_2 + H_2SO_4 + $MgCl_2$ at 200°C), and this value was assumed as total P (Rheinheimer et al. 2003b). Particle size distribution of sediments was determined according to Robert and Tessier (1974). Soil sample dispersion was accomplished with chemical and mechanical treatment, using 0.1 mol L^{-1} NaOH and agitation. Sand fraction was separated by sieving and silt and clay fractions by centrifugation, following the Stokes law.

P desorption capacity was estimated by successive extractions with an AER membrane (Rheinheimer et al. 2003b). Briefly, nonfiltered water and suspended solid samples were transferred to plastic tubes containing an AER saturated with 0.5 mol L^{-1} $NaHCO_3$. The tubes were agitated for 16 h, in an end-over-end agitator at 33 rpm and 25°C. Then, AER membranes were removed, washed with water, and transferred to others plastic tubes containing 10 mL of 0.5 mol L^{-1} HCl. After remaining uncapped for 90 min, the tubes were closed and agitated for 30 min in an oscillating agitator. The P concentration was determined by colorimetric method (Murphy and Riley 1962). This procedure was repeated eight times, since after that the amounts of P became constant and closed to zero.

A first-order kinetic model (McKean and Warren 1996) was employed to fit the desorption curves, allowing the estimate of the potentially bioavailable particulate P (β), the desorption rate constant (λ), and the bioavailable particulate P, which is the P desorbed in the first extraction (α). The model follows Eq. 1, where t is the extraction time, in hours:

$$P_{\mathrm{desorbed}} = \beta - (\beta - \alpha)e^{-\lambda t} \tag{1}$$

The data of sediment concentration, physical and chemical characteristics of sediment, and P desorption parameters (α, β, and λ) were submitted to analysis of variance, considering a split plot design (three subwatershed × two collection point), with six replication (six rainfall events). When the analysis of variance was significant, mean values were compared using Tukey test at the 5% probability level. The correlation coefficients among P desorption parameters and sediment concentration, total organic carbon, and sand, clay, and iron contents were also determined.

3 Results and discussion

3.1 Soil phosphorus availability

The phosphorus contents available in the watershed soils present a wide spatial variability (Fig. 2). Soils belonging to areas with permanent vegetable cover (native forest, reforesting, and natural pasture) present very low and low

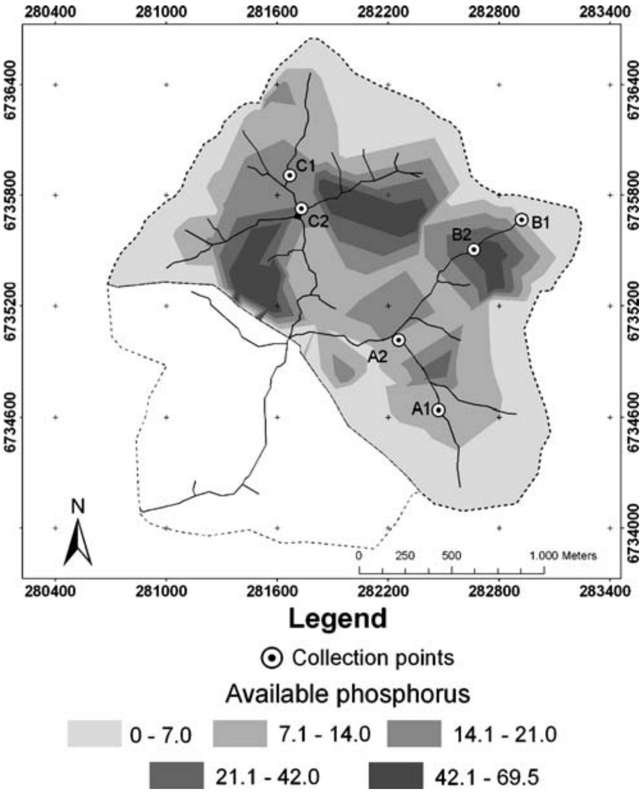

Fig. 2 Phosphorus available in soil surface (0–0.05 m) in Lino watershed, Agudo, RS, Brazil

available phosphorus. Even considering that these soils are relatively young by comparison to the others occurring at subtropical regions, the phosphorus availability is still one of the most limiting chemical factors for crop productivity. Moreover, it is possible to see that some soils that at present are covered with native vegetation were already cultivated in a recent past. As a consequence, their contents of available phosphorus were increased, which certainly contributed to the fast recovery of the native vegetation of the region. Due to the shortage of plain areas for cropping, the farmers deforest declivous lands to tobacco cultivation under conventional soil tillage. After a few years, the organic matter content and structural stability were compromised.

In the subwatershed with permanent cover, the phosphate contamination of superficial waters is low due to the very low soil erosion and the low available phosphorus level. However, these areas contribute sediments with high soluble organic carbon content, which can be used as source of electrons for the reduction process when these sediments were deposited in lentic environments, since these reducing conditions can enhance the availability of the phosphorus adsorbed to the iron oxides.

On the other hand, the cultivated soils of the three subwatersheds have high contents of available phosphorus (see Fig. 2), with amounts even superior to the critical level for maximum economic productivity (CQFS-RS/SC 2004). The crop production system, integrated to the tobacco industry, does not use any technical agronomic–environmental criteria for fertilizing recommendations. The fertilizing doses employed are the same for all the farmers of Southern region of Brazil, independent of soil type, clay content, or historical fertilizer use. Kaiser (2006), for example, had demonstrated that approximately 120 kg N $ha^{-1}year^{-1}$ is not absorbed by the tobacco culture, which represents almost 10,000 kg of N transferred to superficial and mostly subsuperficial aquatic systems in the present small watershed (80 ha of the tobacco). From 9,600 kg $year^{-1}$ of P_2O_5 added in the watershed, not more than 1,000 kg are exported by tobacco leaves (2,200 kg ha^{-1} leaves—Pellegrini (2006) and 0.25% P—Rheinheimer et al. (1991)). The rest remains in the soil, promoting soil P enrichment. In this sense, the combination of inadequate soil use (cultivation on sloping lands and near to water courses) and inadequate management (intensive revolving of soil and low cover levels) with high available phosphorus rates renders the cultivated areas as a great source of sediments (Minella et al. 2007) and phosphorus to the water courses.

The rates of available phosphorus in the studied subwatersheds present a trend to increase from upstream to downstream in the drainage basin. The subwatershed A, where the greatest increase in the rates of available phosphorus was observed, is also characterized by the absence of protection with riparian forest (see Fig. 1), which increases the enriched sediment loads to the water course. In the other two subwatersheds, their soil available phosphorus rates even being higher (see Fig. 2), the presence of a long stretch of riparian forest acts as a buffer zone to the runoff, decreasing the contamination potential of water.

3.2 Sediment concentration and phosphorus forms

The low sediment concentration observed in upstream position (A1=2.8, B1=1.4, C1=2.3 gL^{-1}) is in accordance with the high proportion of forest cover and the low anthropic activity of this area. By contrast, the high concentration of sediments in downstream position (A2=18.0, B2=8.1, C2=6.1 gL^{-1}; Table 2) can be related to the high anthropic activity since 25% of the total surface area is cultivated. The sediment concentration variation among the rainfall events depends on total and intensity precipitation values, as well as on the current soil management. For instance, the rainfall of October 25, 2003 (61 mm) has produced higher sediment concentration (A2=30.9, B2=9.8, C2=7.0 gL^{-1}) than that of December 15, 2003 (83 mm; A2=12.2, B2=6.2, C2=3.4 gL^{-1}), despite its

Table 2 Sediment concentrations and physical and chemical characteristics of sediment in each collection point of the three subwatersheds monitored in Lino watershed, Agudo, RS, Brazil

Subwatershed	Collection point	pH	SC[a] g/L	TOC[b] g/kg	Sand g/kg	Clay g/kg	Fe_d[c] g/kg	Phosphorus (mg/L)		
								Soluble	Available particulate	Total particulate
A	A1	6.7aA	2.8bA	19aA	225aB	200bB	22.8bB	0.09aA	0.13bB	1.55bB
	A2	6.8aA	18.0aA	14bA	150bB	300aA	62.3aA	0.08aA	0.66aA	11.03aA
B	B1	6.5aA	1.4bA	24aA	435aA	280aA	17.6bB	0.05aA	0.24bA	0.87bB
	B2	6.7aA	8.1aB	13bA	145bB	250aB	40.2aB	0.08aA	0.42aB	5.51aB
C	C1	6.7aA	2.3bA	20aA	238bB	170bB	30.8bA	0.10aA	0.26bA	3.31aA
	C2	6.7aA	6.1aB	10bA	280aA	320aA	45.3aB	0.06aA	0.40aB	4.81aB
Coefficient of variation, %		4.6	48.3	20.8	31.3	29.1	17.2	68.7	28.0	40.2

Each value is the average of six rainfall events. Significant differences (Tukey test $P<0.05$) between collection points for each subwatershed are indicated by the small letters (a and b) and between subwatersheds for upstream (A1, B1, and C1) and downstream (A2, B2, and C2) collection point are indicated by the capital letters (A and B)

[a] Sediment concentration

[b] Total organic carbon

[c] Iron extracted by dithionite–citrate–sodium bicarbonate

lower total precipitation. This behavior is due to the fact that, at the end of October, the farmers promote soil mobilization to incorporate N and K fertilizers and weed control. These results are in accordance with those of Lowrence et al. (1998), Leinweber et al. (1999), McDowell et al. (2001b), Reynolds and Davies (2001), and Jordan-Meille and Dorioz (2004) who showed the importance of the soil use and the distribution of cropping areas in the landscape for surface water quality.

Based on the different landscape conformation, we could verify that in subwatershed A the average sediment concentration is higher than that in B2 and C2 (see Table 2). That is probably due to an incipient agriculture in subwatershed B (see Table 1). However, in subwatershed C, despite its similar agricultural surface with A (A=24.7% and C=24.8%), there is a different landscape conformation, where forests in the subwatershed C play a role as contention barriers, especially due to the still-preserved riparian vegetation (see Fig. 1). Thus, the differences observed between A2 (high sediment concentration value) and B2 and C2 (lower sediment concentration values) may be the result of a different distribution of the cultivated areas on the subwatershed surface. In timescale, sediment concentration is related to rainfall intensity, development stage of tobacco, and soil management practices.

High iron contents were systematically found in sediments collected in high-anthropic-activity subwatersheds (A2=62.3, B2=40.2, and C2=45.3 $\mathrm{g kg^{-1}}$; see Table 2). In contrast, the organic carbon content of sediments was lower in these points. Therefore, iron and carbon content seem to be a good integrated indicator of the anthropic activity pressure, besides other factors such as soil type and management.

With regards to P, three forms were evaluated (see Table 2). The average soluble form is high (0.08 mg L^{-1}) and approximately constant from one site to another. This value represents 5.1% and 0.7% of the total P in A1 and A2 collection points of subwatershed A, respectively. The obtained values are much lower than those of Omernik's (1977), which showed that, in forested and cultivated watersheds, soluble P represents more than 60% and less than 40% of total phosphorus, respectively. More recent works in an agricultural watershed in Pennsylvania, USA, have shown that the reactive soluble phosphorus represents in average 31% of the total phosphorus in suspended sediments during storms (Gburek and Sharpley 1998; Sharpley et al. 1999; McDowell et al. 2001a). Available particulate P and total particulate P evaluations were tested as a way to estimate more accurately the impact of anthropic pressures on soil sediments (see Table 2). In the low-activity areas (A1, B1, C1) on the three landscape conformations, the available particulate P is from two to three times lower than that in high-activity ones (A2, B2, C2). The amount of total particulate P was also considerably higher in the areas with more activity, especially in A2 and B2.

3.3 Kinetic aspects of phosphorus mobility

Desorption curves are used to estimate the availability of P in the sediment. The greatest P amounts were desorbed in the first extraction with AER; the following successive

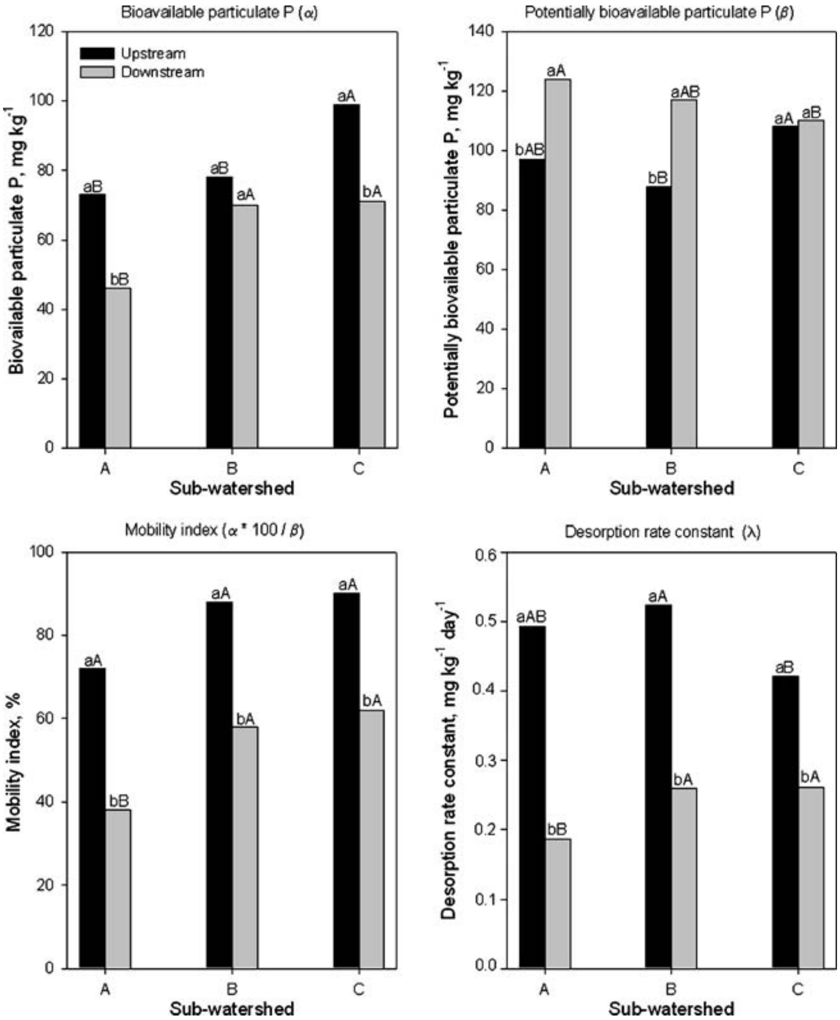

Fig. 3 Bioavailable particulate P (α), potentially bioavailable particulate P (β), mobility index ($\alpha \times 100/\beta$), and desorption rate constant (λ) of sediments in each collection point of the three subwatersheds monitored in Lino watershed, Agudo, RS, Brazil. Each value is the average of six rainfall events. Significant differences (Tukey test—$P<0.05$) between collection points for each subwatershed are indicated by the *small letters* (*a* and *b*) and between subwatersheds for each collection point are indicated by the *capital letters* (*A* and *B*). Coefficient of variation (%): $\alpha=18.5$; $\beta=13.3$; mobility index=17.0; and $\lambda=27.0$

extractions gave rise to an exponential decreasing of the desorbed P. It is possible to see that the amplitude between the first and the second P extraction was always greater in sediments collected in subwatersheds with less anthropic activity (A1, B1, and C1) than those taken from subwatershed with high anthropic activity (A2, B2, and C2). After the second P extraction, only a P amount lesser than 20 mg kg^{-1} remained in the sediment. To achieve the complete removal of P from sediment of watersheds with low and high anthropic activity, four and eight resin extractions were necessary, respectively.

Successive P extractions with AER technique have been used on different soils to asses available P (McKean and Warren 1996; Rheinheimer et al. 2003b). The kinetic model gives three parameters (α, first extractible P; λ, kinetic rate of P desorption; and β, the potentially bioavailable P; Fig. 3). For sediments from low-anthropic-activity areas, α values were higher than those from high anthropic pressure. By contrast, β parameters were greater in the high-anthropic-activity areas than those in low-activity ones. However, the α and β value differences, respectively, in subwatersheds B and C, were not statistically significant ($P<0.05$). Furthermore, β values, which characterize the buffering capacity of the sediment, appeared directly correlated with iron oxide content ($r=0.68$—Table 3). The bioavailable particulate P was negatively correlated with sediment concentration ($r=-0.79$, see Table 3). This behavior can be explained by the increase in silt and sand particles (>2 μm) in the sediment. In high-runoff conditions, the greater amounts of iron oxides cause a diminishing of short-term P availability. By contrast, it was observed that α values were directly related to the amount of total organic carbon (see Table 3). These results suggest that P associated to iron oxides is sufficiently stable and that iron oxides at least partly control the adsorption and desorption properties of P in the sediments. As a consequence, this stable form can be transported for a long distance and remaining stable for a long time, depending on the oxidation–reduction conditions (Favre et al. 2004).

The ratios between α and β can also be useful in defining a mobility index related to the pollution type (see Fig. 3). The α/β ratios were higher in low-anthropic-

Table 3 Correlation coefficients between sediment concentration, total organic carbon, sand, clay, and iron contents, and bioavailable particulate P (α), potentially bioavailable particulate P (β), and desorption rate constant (λ) in Lino watershed, Agudo, RS, Brazil

Parameters	Bioavailable particulate P (α)	Potentially bioavailable particulate P (β)	Desorption rate constant (λ)
Sediment concentration	−0.79*	0.52 ns	−0.60*
Total organic carbon	0.65*	−0.27 ns	0.74**
Sand	0.48 ns	−0.29 ns	0.46 ns
Clay	−0.25 ns	0.08 ns	−0.12 ns
Fe_d[a]	−0.52 ns	0.68*	−0.89**

ns not significant

**P*<0.05; ***P*<0.01

[a] Iron extracted by dithionite–citrate–sodium bicarbonate

activity areas (72%, 88%, and 90%) than those in areas of high anthropic activity (38%, 58%, and 62%), indicating that the sediment originating from high forest cover desorbed P more easily than that originating from cultivated land. The desorption rate constants (λ) were higher in low-anthropic-activity areas, i.e., A1, B1, C1, λ (0.493, 0.524, and 0.421 mg $kg^{-1}day^{-1}$), than that in high-anthropic-activity areas, i.e., A2, B2, and C2, λ (0.186, 0.259, and 0.261) mg $kg^{-1}day^{-1}$, respectively. In sediments collected from subwatersheds with low anthropic activity, phosphate ions were released to solution, on average, twice as rapidly as those from subwatersheds with high anthropic activity (see Fig. 3). The λ value is related directly to total organic carbon ($r=0.74$) and inversely to the sediment concentration ($r=-0.60$) and iron content ($r=-0.89$; see Table 3).

Concerning P forms in sediments, it seems that the soluble P concentration is a poor indicator of the potential pollution of soil sediments. However, P desorption can be used to assess P availability and reliability potential for water eutrophication. Rheinheimer et al. (2003b) showed that for subtropical soils six to 11 extractions were necessary to remove potentially available P.

The values of desorbed P obtained by desorption studies carried out on sediments are systematically higher than the analogous ones on soils. This fact can be explained in part by an enrichment of sediments with organic carbon and clay, which affects the natural selectivity of the runoff. Another important factor is the pollution source type, such as those ones due to the various types of animal breeding that contributes to P enrichment, as shown by Sharpley et al. (1995) and Dils and Heathwaite (1996). Additionally, chemical and mineralogical characteristics such as the high pH of water, the relatively low amounts of iron (see Table 3), and the predominance of 2:1 clays in the 2 μm fraction of sediment (Bortoluzzi 2004) may also facilitate sediment P desorption.

In cultivated soils, in which P is preferentially adsorbed on iron oxides, a slow P desorption is usually observed, even when the content of this element is high. However, when these sediments will be deposited in lakes and reservoirs, the P desorption dynamics will change (Correll 1998). This behavior is due to the oxy-reduction process, which leads to a gradual dissolution of iron oxides by reducing Fe^{+3} to the soluble ion Fe^{+2}, releasing the adsorbed phosphate ions. Therefore, the potential contamination of sediment is better correlated to β values (Correll 1998; Koski-Vähälä and Hartikainen 2001).

4 Conclusions

From the present work, it can be concluded that a typology of the landscapes is a useful tool to analyze anthropic pressures and their impact on ecosystems. However, to assess such impact, it does not suffice to know the proportion of soils with their different land uses (cropping systems, forests, prairies, orchards) in a landscape. One of the key points in analyzing soil and sediment erosion and its consequences is a description of the different aspects of land planning, such as the position of agricultural fields and the extent of protection zones along streams. As a consequence, the obtained results highlight the importance of regional planning, especially with regards to the degree of occupation of the landscape itself, on the attempts to minimize environmental impacts. The types and the magnitude of contamination can be better determined when the typology of anthropic activity is considered. However, it does not suffice to know the total amount of soluble or total P to evaluate an environmental impact. Information on kinetics is invaluable for assessing the spatial and temporal magnitude of the pollution.

In this sense, in a scenario of landscape with low anthropic activity, like in subwatershed B, with a small proportion of cultivated soils and adequate watershed planning in a forest context, in general, the sediment contamination is low. However, in these conditions, P can be very mobile and bioavailable due to the organic matter enrichment of soil sediments. In contrast, in a scenario of high anthropic activity, the concentration of sediments carried out by the runoff is high and the amount of solid particles in water is a key parameter to evaluate soil degradation. This parameter is important for predicting transfers of chemical elements as well as organic substances in the environment. The sediments eroded from high-anthropic-activity areas showed high iron concentrations and low carbon content. As a consequence, the potential contamination in a long-term perspective seems to be high. Hydrologic events should be monitored in order to assess the efficiency of practices and management.

5 Recommendations and perspectives

This study showed that the cultivation of tobacco in agricultural highland, involving intensive soil preparation, leads to a great soil erosion and phosphorus transferred to superficial water bodies. The contamination of water by phosphates is facilitated by the presence of tobacco cropping areas located near streams. Since the higher amount of phosphorus transferred from soil to water bodies appears in the particulate form, urgent measures for erosion control must be adopted. Among them, it is worth pointing out the adoption of a conservation crop system, regeneration of riparian zone, and the reduction of the phosphate doses added to soil for tobacco cultivation.

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