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Seasonal changes in inorganic and organic phosphorus in the soil of a riparian forest

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Abstract. This study addresses the temporal distribution of forms of phosphorus in the soil of a temporarily flooded riparian forest of the valley of the river Garonne (Southwest of France). A sequential extraction for forms of phosphorus of increasing chemical stability was used. During the study period (13 months), the forest was flooded a few days during March and May. In winter, resin-Pi concentration was high (26 $\mu g\ g^{-1}$) in comparison to spring values (<9 $\mu g\ g^{-1}$). $NaHCO_3$-Po, $NaHCO_3$-Pi or NaOH-Pi concentrations increased during winter (up to 74, 124 and 78 $\mu g\ g^{-1}$ respectively) and decreased significantly during spring (32, 44 and 32 $\mu g\ g^{-1}$ respectively). This pattern was attributed to simultaneous mineralization and plant uptake during the growing season and to the flood events (erosional processes and P-release). During summer and fall, resin-Pi concentration increased significantly (up to 26 $\mu g\ g^{-1}$ in October). $NaHCO_3$-Po concentrations remained low during spring and summer (<33 $\mu g\ g^{-1}$), and increased significantly in fall (>45 $\mu g\ g^{-1}$). $NaHCO_3$-Pi or NaOH-Pi increased in late spring or summer (90 $\mu g\ g^{-1}$ and 68 $\mu g\ g^{-1}$ respectively). Increasing concentrations of the labile forms during late spring or summer were ascribed to the warm temperature and soil dryness that limited plant growth. HCl-Pi increased regularly after the floods (174 $\mu g\ g^{-1}$ before the flood events to 254 $\mu g\ g^{-1}$ after the floods). Residual P presented a similar pattern i.e. 214 $\mu g\ g^{-1}$ and 279 $\mu g\ g^{-1}$ respectively before and after the flood events. This pattern was attributed to a progressive incorporation of flood deposits to the soil.

Introduction

It is now well established that phosphorus is distributed in soils between different forms with different pedological, biological or ecological significance and that the content and proportions of these different forms depend on numerous factors (Smeck 1985). Distribution of soil phosphorus through vegetation categories has been investigated in different geographical areas (Uzu et al. 1975; Harrison 1979; Mitchell et al. 1984; Mahendrappa et al. 1986; Sattell & Morris 1992; Yanai 1992; Tchuenteu 1994). Some studies have focused on the distribution of phosphorus along toposequences (Adams & Walker 1975; Gregorich & Anderson 1985; Roberts et al. 1985) and chronosequences

(Syers & Walker 1969; Lajtha & Schlesinger 1988) or on the effect of natural drainage conditions (Runge & Riecken1966). The effects of cultivation were also investigated (Hedley et al. 1982; Tiessen et al. 1983; Tracy et al. 1990). Most of these studies address the long term evolution of soils in the context of various landscape or pedological factors (Smeck 1985; Stewart & Tiessen 1987). Short term studies are mainly laboratory studies in which the effects of carbon or plant residue are investigated (Chauhan et al. 1979, 1981; Hedley et al. 1982; White & Ayoub 1983). Some studies address sampling problems associated with the estimation of the requirements of P fertilizers in agricultural applications (Malhi et al. 1991; Nyborg 1992) and are generally limited to plant available P. However, we have very little detailed information on the variation of forms of phosphorus in soils on a monthly basis.

In riparian forests, most studies have focused on their effectiveness in controlling nutrient loss from agricultural land to streams (Omernik et al. 1981; Peterjohn & Correll 1984; Cooper & Gilliam 1987). Moreover, in most of the studies concerning phosphorus in riparian forests, only some forms of phosphorus are considered (Sanchez-Pérez et al. 1993). This study addresses the temporal distribution on a monthly basis of forms of inorganic and organic phosphorus in the soil of a riparian forest. It is a part of a programme concerning the study of the corridor of the River Garonne, Southwest of France (Probst 1985; Chauvet & Fabre 1990; Fabre 1992; Pinay et al. 1992, 1995).

Study site

The River Garonne has its source in the Pyrenees mountains (altitude 2850 m). The watershed is successively formed of plutonic rocks, carbonated rocks and detritic deposits. In the upper part, the landscape consists of beech and coniferous forests, whilst agricultural activities predominate in the lower part. The River Garonne presents a nival transitional regime with maximum discharge in spring due to precipitation and snow melt. The low water period generally lasts from August to October, with discharge <20 m^3 sec^{-1}, while the mean annual discharge is 200 m^3 sec^{-1}. A riparian forest was chosen, downstream of the town of Toulouse (altitude 95 m). During the 13 months of the study, the site was flooded twice (with a peak discharge of 963 m^3 sec^{-1} in March 91, and 1510 m^3 sec^{-1} in May 91). The P dissolved concentration in the water column varied between 20 and 50 μg l^{-1}. During floods, high current velocity (0.1 m s^{-1}) reduced fine particle deposition and led to deposition of coarse sediments. The soil is flat and dominated by sand (43.6%) and silt (48.5%), with clay representing only 7.9% of the total grain size fractions (Pinay et al., 1992). The soil is a Fluvent. The vegetative cover is mainly composed of willows (*Salix alba*), poplar (*Populus alba*), with few ashes

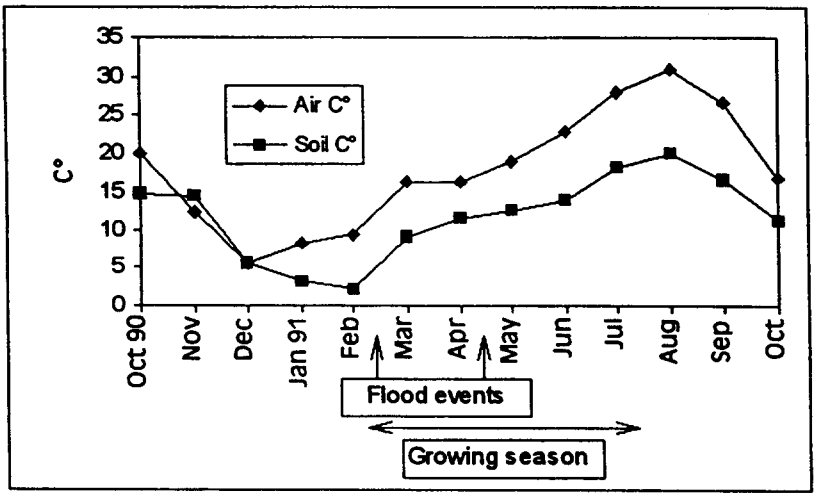

Figure 1. Monthly air and soil temperature.

(*Fraxinus excelsior*) or elms (*Ulmus campestris*). The understory community was mainly composed of *Urtica dioica, Brachypodium sylvaticum, Carex maxima, Galium aparine* and *Lamium maculatum.* During the study period, the mean air temperature ranged from 5.7 °C in December to 30.9 °C in August, whilst the soil temperature (−10 cm) ranged from 2.2 °C in February to 20.1 °C in August (Figure 1). During winter the soil was often covered by frost. The growing season lasted from February to July or August. The understory vegetation began to grow between February and March. April and May correspond to the period when the trees come into leaf. During summer, the herbaceous were decaying and the tree growth could have been limited by temperature and soil dryness.

Materials and methods

Sampling method

The forest soils were sampled monthly between October 1990 and October 1991. Each month, 8 sampling units constituting 8 replicates of one square meter were randomly selected (only 4 during October 1991). In each sampling unit, about 1 kg of soil was extracted from the top ten centimeters after the litter was discarded. After the floods, sediments deposited on the riparian forest floor were sampled (5 replicates). After collection, all the soil samples were stored at 4 °C until analyses were performed within a few days.

Sequential phosphorus extraction

Soil P was fractionated using the procedure developed by Hedley et al. (1982) but with some simplifications. The sequential extraction removed inorganic P (Pi) and organic P (Po) of increasing chemical stability. The most labile inorganic phosphorus was extracted first with an anion exchange resin (resin-Pi) (Amer et al. 1955). Sodium bicarbonate 0.5M (pH 8.5) removed labile Pi ($NaHCO_3$-Pi) and Po ($NaHCO_3$-Po) sorbed to the soil surfaces (Bowman & Cole 1978 a, b). $NaHCO_3$-Po is easily mineralizable and can contribute to plant available P. Extraction of microbial P was not performed. However, $NaHCO_3$ extraction may release some P from microbial cells (Hedley & Stewart 1982). Sodium hydroxide 0.1M extracted Pi (NaOH-Pi) associated with amorphous and some crystalline Al and Fe oxides (Syers et al. 1969) and Po (NaOH-Po) associated with humic compounds (Fares et al. 1974). NaOH-Pi is relatively labile Pi (Bowman & Cole 1978 a, b) while NaOH-Po is considered to be involved in long term transformation of soil P under temperate climates (Tiessen et al. 1983). Phosphorus extracted with hydrochloric acid 1M (HCl-Pi) is mainly constituted by apatitic phosphorus. It is unavailable in the short term. The residue containing the most chemically stable Po and Pi forms (residual-P) was digested using concentrated H_2SO_4+H_2O_2 (Thomas et al. 1967). Due to technical reasons, ultrasonification of the soil residue after NaOH extraction and subsequent extraction with NaOH, as recommended by Hedley et al. (1982) were not performed. In such condition part of Pi and Po held at the internal surface of soil aggregates was probably extracted during the HCl and H_2SO_4+H_2O_2 steps. Extracts containing organic phosphorus were digested for total P determination using persulfate digestion method (Standard Methods 1971). Phosphorus in the extracts or digests was determined after pH adjustment if necessary, using ascorbic acid molybdenum blue method (Murphy & Riley 1962). In this paper when necessary we considered only the sum of the more or less labile forms of phosphorus i.e. resin-Pi, $NaHCO_3$-Pi, $NaHCO_3$-Po and NaOH-Pi (labile-P), or the sum of more or less stable forms i.e. HCl-Pi and residual-P (stable-P).

Statistical methods

Cluster analysis was used to identify statistical relations between forms of phosphorus. The amalgamation method used was the single linkage clustering method (Everitt & Dunn 1990).

Global differences between monthly values for each phosphorus form were tested using ANOVA. Subsequently when necessary, individual paired differences were tested using the Scheffé method to detect significant differences between months (Dowdy & Wearden 1991). To test differences

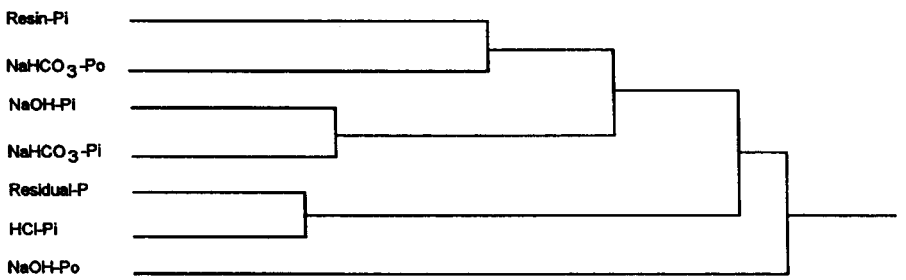

Figure 2. Dendrogram for the extracted forms of soil phosphorus.

between P concentrations in the soil and in the sediments deposited by the floods, the Dunnett test was used, considering sediment concentrations as a control group. For all reported results we considered only significant statistical differences at P level <0.05. Statistical analyses were performed using SYSTAT software (SYSTAT 1992).

Results

Relationships between forms of phosphorus

Cluster analysis applied to all the seven forms of phosphorus showed 4 groups (Figure 2). Resin-Pi and $NaHCO_3$-Po as well as NaOH-Pi and $NaHCO_3$-Pi constituted two groups clearly separated from a group constituted by residual-P and HCl-Pi. The fourth group was constituted by NaOH-Po alone and appeared to be more related to the stable forms than to the labile ones. Each group showed a particular temporal pattern.

Temporal evolution of the forms of phosphorus in the soil (Table 1, Figure 3)

During the study period, the sum of the P fractions varied from 562 $\mu g\ g^{-1}$ in March to 844 $\mu g\ g^{-1}$ in August. Between February and March, soil P content decreased markedly from 729 $\mu g\ g^{-1}$ to 562 $\mu g\ g^{-1}$. Taken as a whole, the P concentrations from May to October 91, i.e., after the second flood, were significantly higher than the concentrations from October to February 90. P concentrations in October 90 and October 91 differed significantly (607 and 755 $\mu g\ g^{-1}$ respectively) (Table 1). During the period considered, percentage contribution of labile-P to the sum of the fractions, varied between 40.7% in January to 20.4% in March. Stable-P represented more than 50% to the sum of the fractions and varied from 55% in January or February to 70% in August. The lower contributions corresponded to NaOH-Po and varied between 4.3% in January and 5.9% in October 90 (Table 1).

Table 1. Monthly mean values ($\mu g\ g^{-1}$), standard error of the mean (n = 8, except on October 91, n = 4) of phosphorus in sequential extraction of soil forest, sum of forms of similar stability and percentage contribution to the total pool.

	Oct 90	Nov 90	Dec 90	Jan 91	Feb 91	Mar 91	Apr 91	May 91	Jun 91	Jul 91	Aug 91	Sep 91	Oct 91
Resin-P	23.4	27.9	24.3	28.1	28.5	6.8	6.8	8.6	7.8	16.6	21.0	23.9	26.0
	±0.68	±0.90	±1.31	±2.19	±1.28	±0.25	±0.53	±0.57	±0.37	±1.03	±0.46	±0.44	±0.71
$NaHCO_3$-Pi	75.9	66.4	76.0	105.0	123.5	44.1	74.6	88.5	95.6	92.5	87.5	89.9	75.3
	±5.66	±5.45	±3.33	±5.68	±3.73	±2.87	±3.43	±2.66	±2.81	±3.31	±3.12	±9.96	±2.72
$NaHCO_3$-Po	39.8	41.0	59.6	74.1	67.3	31.8	31.8	32.6	28.3	31.8	32.4	48.3	46.0
	±2.93	±2.54	±4.37	±4.51	±4.78	±3.37	±1.57	±2.32	±3.00	±2.72	±4.27	±0.88	±1.58
NaOH-Pi	49.8	48.3	55.6	78.1	75.3	31.5	43.8	64.1	68.6	68.4	68.1	64.9	53.5
	±1.37	±3.48	±3.61	±3.28	±3.67	±1.76	±2.54	±2.20	±3.69	±1.80	±2.23	±4.32	±2.63
Sum of labile forms	188.9	183.6	215.5	285.3	294.6	114.2	157.0	193.8	200.3	209.3	209.0	227.0	200.8
% of labile forms	31.2	32.6	35.2	40.7	40.4	20.4	24.7	27.8	27.0	26.4	24.8	27.6	26.6
NaOH-Po	35.6	26.5	28.9	30.5	32.5	28.5	33.0	26.5	25.4	39.9	42.4	38.3	37.0
	±3.26	±2.16	±2.74	±3.10	±2.87	±1.99	±2.17	±3.46	±3.72	±1.53	±1.40	±1.00	±1.78
% NaOH-Po	5.9	4.7	4.7	4.3	4.5	5.1	5.2	3.8	3.4	5.0	5.0	4.6	4.9
HCl-Pi	178.3	168.9	176.8	178.1	169.6	205.7	200.6	215.1	239.3	254.9	289.3	276.3	250.0
	±5.28	±10.0	±4.81	±6.03	±5.49	±7.93	±5.13	±4.61	±4.25	±5.02	±5.29	±6.57	±11.2
Residual- P	204.1	184.6	191.5	207.4	231.9	213.5	246.4	258.9	275.3	288.5	303.6	282.5	267.0
	±6.60	±6.49	±4.60	±8.55	±8.93	±4.92	±4.8	±5.84	±7.69	±3.01	±3.35	±11.10	±6.72
HCl-Pi + residual P	382.4	353.5	368.3	385.5	401.5	419.2	447.0	474.0	514.6	543.4	592.9	558.8	517.0
% HCl-Pi + residual P	63.0	62.8	60.2	55.0	55.1	74.6	70.2	68.3	69.5	68.6	70.3	67.8	68.5
Sum of the fractions	606.8	563.5	612.6	701.4	728.6	561.9	636.9	694.4	740.2	792.6	844.3	824.0	754.7

Between October 90 and February 91, resin-Pi presented stable concentrations (around 26 $\mu g\ g^{-1}$). A decrease occurred in March and resin-Pi concentrations remained very low (<9 $\mu g\ g^{-1}$) until June. From July, resin-Pi concentration increased significantly until October 91, when it returned to values measured in October 90 (Figure 3a). $NaHCO_3$-Po concentrations were significantly higher than resin-Pi. However, apart from an increase during winter (December, January), $NaHCO_3$-Po presented a pattern similar to resin-P. Again, in October 90 and October 91, $NaHCO_3$-Po concentrations did not differ significantly (Figure 3a).

$NaHCO_3$-Pi and NaOH-Pi presented similar distribution during the study period (Figure 3b). From October 90 to December 90, $NaHCO_3$-Pi concentrations remained around 73 $\mu g\ g^{-1}$. During January and February the concentrations increased to 124 $\mu g\ g^{-1}$. March was characterized by an important decrease (44 $\mu g\ g^{-1}$) followed by an accumulation from April (75 $\mu g\ g^{-1}$) to June 91 (96 $\mu g\ g^{-1}$). NaOH-Pi concentrations remained around 51 $\mu g\ g^{-1}$ from October 90 to December 90, increased in winter (around 77 $\mu g\ g^{-1}$ in January and February) and decreased in March (32 $\mu g\ g^{-1}$). In May the concentrations increased (64 $\mu g\ g^{-1}$) and remained stable until October 91 where they reached the value measured in October 90.

NaOH-Po concentrations remained low throughout the study showing irregular fluctuations from November 90 to June 91 (around 29 $\mu g\ g^{-1}$) (Figure 3c) and increasing significantly in July (40 $\mu g\ g^{-1}$). The concentrations from November 90 to June 91 were significantly lower than the concentrations from July to October. However, NaOH-Po concentrations in October 90 and October 91 were not significantly different.

HCl-Pi concentrations were stable between October 90 and February 91 (around 174 $\mu g\ g^{-1}$), then increased regularly from March (206 $\mu g\ g^{-1}$) to August (289 $\mu g\ g^{-1}$). Concentrations measured before the flood events i.e. March and May, were significantly lower than those measured after the flood events (around 174 and 254 $\mu g\ g^{-1}$ respectively). Residual-P presented a similar temporal pattern. From March to August, the concentrations increased regularly (from 214 $\mu g\ g^{-1}$ in March to 304 $\mu g\ g^{-1}$ in August). Concentrations measured before the flood events were also significantly lower than those measured after the flood events (around 204 and 279 $\mu g\ g^{-1}$ respectively). Moreover, HCl-Pi and residual-P concentrations in October 91 were significantly higher than in October 90 (Figure 3d).

Forms of phosphorus in the sediments deposited by the floods

The sum of the fractions represented 593 $\mu g\ g^{-1}$. Labile-P, NaOH-Po and stable-P represented respectively 23.8, 4.9 and 71.2% of the sum of the fractions (Table 2). Compared to the monthly soil concentrations, labile-P

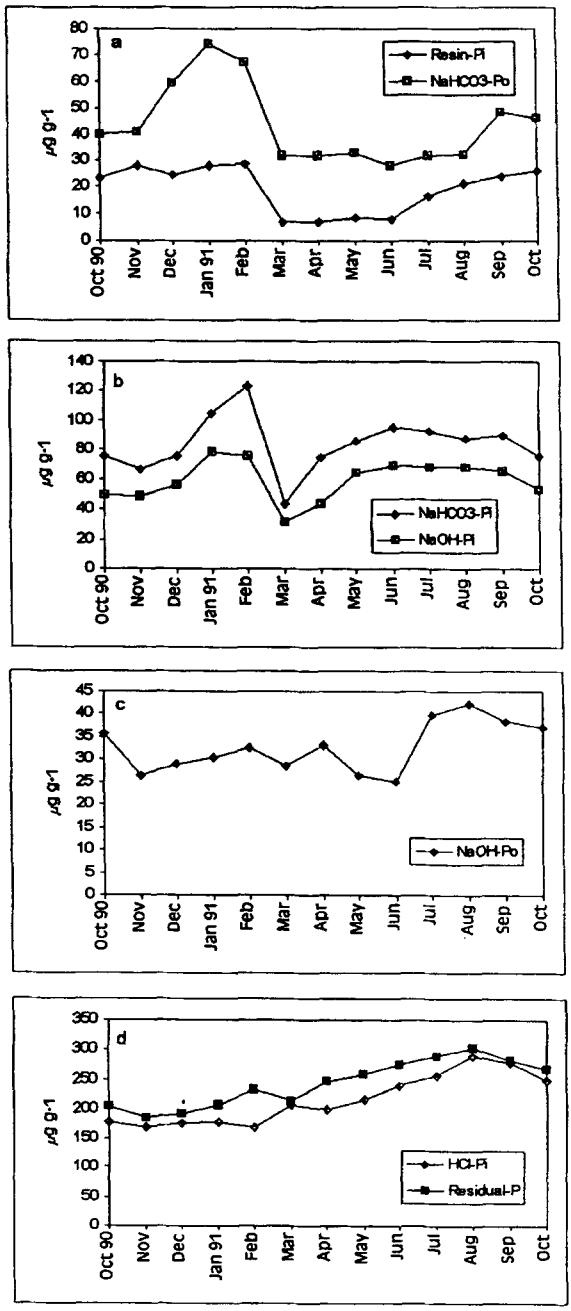

Figure 3. Monthly mean values of the extracted forms of soil phosphorus.

Table 2. Mean values ($\mu g\ g^{-1}$), standard error of the mean and percentage contribution to the total P-pool of different forms of P in the sediments deposited during the floods (n = 5),

	Labile-P	NaOH-Po	HCl-P + residual P	Sum of the fractions
Mean	141.9	29.0	421.8	592.8
SEM	18.1	2.1	13.1	11.4
% of the total pool	23.8	4.9	71.2	

was significantly lower in the sediments deposited by the floods, except during March and April where the concentrations were not significantly different. Stable-P concentration in the sediments was significantly higher than concentrations in the soil measured in November and December 90, and significantly lower from May to October 91. From January to April, concentrations were not significantly different. The riparian soil and the deposited sediments did not present any significant differences in NaOH-Po concentration.

Discussion

All the labile forms of phosphorus presented a similar temporal pattern with stability or accumulation during winter, an important decrease in March and low values in spring. The accumulation of the most labile forms of phosphorus during winter and their decrease during the growing season is in accordance with other results found in the literature (Saunders & Metson 1971; Vaughan et al. 1986; Sorn-Srivichal et al. 1988; Sarathchandra et al. 1989; Perrott et al. 1990; Buchanan & King 1992).

Plant residue or litter leaching are generally considered as a source of labile-P (Timmons et al. 1970; Bromfield & Jones 1972; Blair & Boland 1978; Laflen & Tabatabai 1984; Weiss et al. 1991). Release of phosphorus is attributed to the plant or microbial cell decaying through biological or physical processes such as frost (Timmons et al. 1970). In this study, we can hypothesize that the significant increase of $NaHCO_3$-Pi, NaOH-Pi and $NaHCO_3$-Po concentrations during winter was a consequence of P leaching from fresh litter (leaf fall) accumulated from November to January and to the limitation of mineralization processes during winter low temperatures.

Decrease of labile-P during March and the low concentrations of resin-P and $NaHCO_3$-Po during spring are ascribed to microbial and plant uptake. Inorganic labile-P pool is not only depending on microbial and plant uptake, but also on the mineralization of organic form such as $NaHCO_3$-Po that is considered to be easily mineralizable. Generally, it is considered that soil

organisms can use labile Po and, through cell turnover, convert non-extractable forms to plant available phosphorus (Paul & Clark, 1989). Under these conditions, the amount of inorganic and organic labile P results from interactions between mineralization and uptake processes, which depend on climatic factors i.e. soil and air temperature, precipitation and soil moisture. Increasing soil temperature during March (2°C in February and 9 °C in March) can lead to the mineralization of organic phosphorus with subsequent uptake by plants during spring, when the herbaceous and shrub understory and the trees come into leaf.

Nevertheless, the decrease of the labile forms of phosphorus was very important between February and March and cannot be explained by microbial and plant uptake only. Effects of hydrological factors related to the flood events can be hypothesized. Several authors have pointed out the relationship between the finer soil particles and the labile forms of phosphorus and inversely between the coarse particles and apatitic phosphorus (Tiessen et al. 1983; Sharpley et al. 1981; Stone & English 1993). In our study site, dominated by high water velocity during floods, the soil content has a low percentage of finer particles and, consequently, the relative contribution of labile-P during such event is reduced. Inversely, coarse particle deposits from floods could increase the relative contribution of apatitic-P and possibly of residual-P. Moreover, a part of the decrease of labile-P can also be ascribed to the release of the most labile forms of P from the soil particles to the water column. Uptake or release of phosphorus by sediments or soils is the result of a complicated interaction between physical, chemical, and biological factors (Syers et al. 1973). Among all the investigated factors, it appears that P release by sediments or soils is stimulated by low P-content in the overlying or interstitial water (Kamp-Nielsen 1974). Hence, the low P water concentration during floods of the River Garonne could cause release of a part of labile phosphorus from the soil particles to the water column.

The regular increase of stable-P concentration since April and the increase of NaOH-Po concentration from July suggest a progressive incorporation of the sediments deposited during flood, by summer storms or through the soil fauna's ingestion/dejection processes.

Conclusion

The evolution pattern of P concentration in the riparian soil varied significantly among the different forms considered. The most labile forms were highly dependent on seasons with stabilization (resin-Pi) or important accumulation during winter ($NaHCO_3$-Po, $NaHCO_3$-Pi and NaOH-Pi). Stabilization or accumulation were ascribed to the cold winter temperature,

to the decay of leaves and the leaching of labile forms of P from the litter. During spring, all these forms decreased markedly. This temporal pattern is related to mineralization processes ($NaHCO_3$-Po) as related to an increase of temperature during spring, to plant uptake (resin-Pi, $NaHCO_3$-Pi) and to the effect of the flood events i.e. erosional processes and P release. During summer, the relative stability or regular accumulation of the labile forms of phosphorus can be ascribed to the warm temperatures, corresponding to a period of limited vegetation growth. During the 13 month study, these labile forms of phosphorus presented significant variations, but remained rather stable from year to year (similar concentrations in October 90 and October 91). On the contrary, HCl-Pi and residual-P changes were independent of the seasons and only related to the flood events.

In terms of P cycling, floods events were an important ecological factor in the riparian forest. On the one hand, floods contributed to the decrease of labile-P pool. Hence, the riparian forest can be considered as a temporary source of phosphorus for the river. On the other hand, floods contributed to the increase of stable-P and the riparian forest could be considered as a phosphorus sink. However, from an ecological point of view, the role of riparian forest as a source of P for the river is probably the most important since it concerns easily bioavailable forms of P.

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