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Sediment production and water quality of watersheds with contrasting land use in Navarre (Spain)

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ABSTRACT

An experimental watershed (Oskotz principal– Op –ca.1700 ha) covered with forest and pasture (cattle-breeding) with an equally experimental sub-watershed (Oskotz woodland – Ow – ca. 500 ha) almost entirely under forest was continuously monitored during 8 years (2001–2008). These watersheds were established by the Government of Navarre (Spain) in order to assess the impact of agricultural activities on different region of Navarre. The first results regarding exported sediment, runoff, nitrate and phosphate are presented herein. These results are compared with those from two grain-sown watersheds previously reported by the authors, elsewhere.

The same as in the grain-sown watersheds, most runoff, sediment, nitrate and phosphate yields in Oskotz were generated during winter, though most erosive rainfalls occurred during summer. In Ow, average sediment, nitrate and phosphate yields were approximately: 700, 22, 0.35 kg ha year^{-1}, respectively; for Op these figures were 550, 54 and 0.76 kg ha year^{-1}, respectively.

However, total sediment and solute yields were different depending on the prevailing land use: cereal crops > forest > pasture. Sediment yields in the forest were strongly affected by the logging moment, when exported sediment rocketed.

Nitrate concentration and yields were lower (and under the critical threshold) in the forested/pastured watersheds than those recorded in the two intensively cultivated watersheds. However, phosphate yields were dramatically higher (and over the critical threshold) in the former watersheds due to the prevailing soil conditions and to the fertilization of pasture, mainly with slurry.

The present work, along with that similar one recently reported by the authors, is an unprecedented and relevant piece of research for the region.

1. Introduction

Soil erosion is a serious and common problem of non-irrigated arable lands in Europe (Poesen et al., 2003; Auzet et al., 2004; Boardman and Poesen, 2006; García Ruiz and López Bermúdez, 2009), where approximately a quarter of its agricultural land exhibits some erosion risk (EEA, 2005). Erosion causes soil degradation and also severely affects water resource quality. Moreover, the so-called non-point source pollution due to nitrate and phosphate is predominant in agricultural areas. For instance, agriculture is the source of 46–87% of the nitrate and 20–40% of the phosphate incorporated into European continental waters (EEA, 1999).

In Navarre (Spain), soil erosion is an important problem present in its agricultural lands (Casalí et al., 1999; De Santisteban et al., 2006; García Ruiz and López Bermúdez, 2009). For that reason, the Department of Agriculture, Livestock and Food of the Government of Navarre established a network of experimental grain-sown watersheds in order to provide data for assessing the effect of agricultural activity on erosion and water quality. Additionally, this information is of great utility to identify and evaluate environmentally sound land management practices and as an invaluable database for evaluating hydrological models (García Ruiz and López Bermúdez, 2009). The experimental watershed network consists of 4 watersheds (namely Latxaga, La Tejería, Oskotz and Landazuria). The instrumentation in each watershed includes: one automatic weather station; several non-recording rainfall gauges distributed throughout the watershed; and one hydrological measuring station, where discharge, turbidity and water quality parameters are measured (Casalí et al., 2008). The geological material is impervious within each watershed, which ensures an acceptable control of the water balance.

The hydrological behaviour and water quality data of Latxaga and La Tejería watersheds, representative of wide areas of Navarre

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and northern Spain as regards their morphology, climate, land use (winter grain crops) and management, were recently analyzed in detail by Casalí et al. (2008) after almost a decade of data collection. Casalí et al.'s findings showed clear differences in the behaviour of both watersheds, especially in terms of sediment and nitrate concentration and yield. Those differences were unexpected since both watersheds are close to each other with respect to soils, land use and management practices. However, the authors stated that some differences, mainly in watershed morphology and topography as well as vegetation on stream channels, largely accounted for the discrepancy observed between both sites.

In this paper, data recorded at Oskotz watershed are now similarly analyzed and studied in detail (cf. Casalí et al., 2008). The information already available for this watershed covers around 8 years with continuous observations: from September 2001 to May 2009. Rainfall, runoff, sediment, nitrate and phosphate data are presented and discussed. It should be noted that unlike Laxtaga and La Tejería, which are devoted to grain crops (Casalí et al., 2008), Oskotz is a watershed dedicated to cattle-breeding with a sub-watershed covered mostly with forest. This may allow us, by comparative analysis, to gain insight into the land use as a main controlling factor affecting the hydrological behaviour of our watersheds.

The remaining experimental watershed, i.e. Landazuria, is not dealt with herein. The reason is that the corresponding dataset still has an insufficient amount of recorded years to allow similar analysis. Besides, the hydrological behaviour of Landazuria deserves to be analyzed apart since it is an irrigated, intensively cultivated watershed.

Therefore, the main objectives of this paper were (1) to analyze the behaviour of forested/pastured experimental watersheds in terms of discharge, sediment, nitrate and phosphate yield and concentrations and (2) to study the controlling factors underpinning that behaviour. To do that, comparisons with contrasting watersheds – mainly in terms of land use, grain crops – previously studied by the authors were carried out.

2. Description of the experimental watersheds

The experimental watershed of Oskotz comprises 1674 ha in the northeastern part of Navarre (Spain) (Fig. 1) with an altitude ranging from 924 to 530 m.a.s.l. Its climate is sub-Atlantic, with an average annual precipitation of 1200 mm, distributed over 130 days of rainfall, and an average annual temperature of 12 °C (Gobierno de Navarra, 2001). The main morphological characteristics of the watershed are shown in Table 1. The hillslopes are in the range of 10–65% but only around 5% in the valley bottom. Geologically, the area is underlined by clay marls and Pamplona grey marls (Gobierno de Navarra, 1997). A detailed soil map (USDA Soil Taxonomy, 2010) of the Oskotz watershed is provided in Fig. 2, and information on soil properties in Table 2. The prevailing soil classes are distributed according to the landscape's position. That is, eroded hillslopes are occupied by Lythic and Typic Ustochrepts, accumulation hillslopes by Typic Ustochrepts, and the valley plain by Fluventic Ustochrepts. Soils are fine and more than 1 m deep except for those in the eroded hillslope that are shallow (0.5–1 m deep). Most of the watershed is covered with forest (1021 ha,

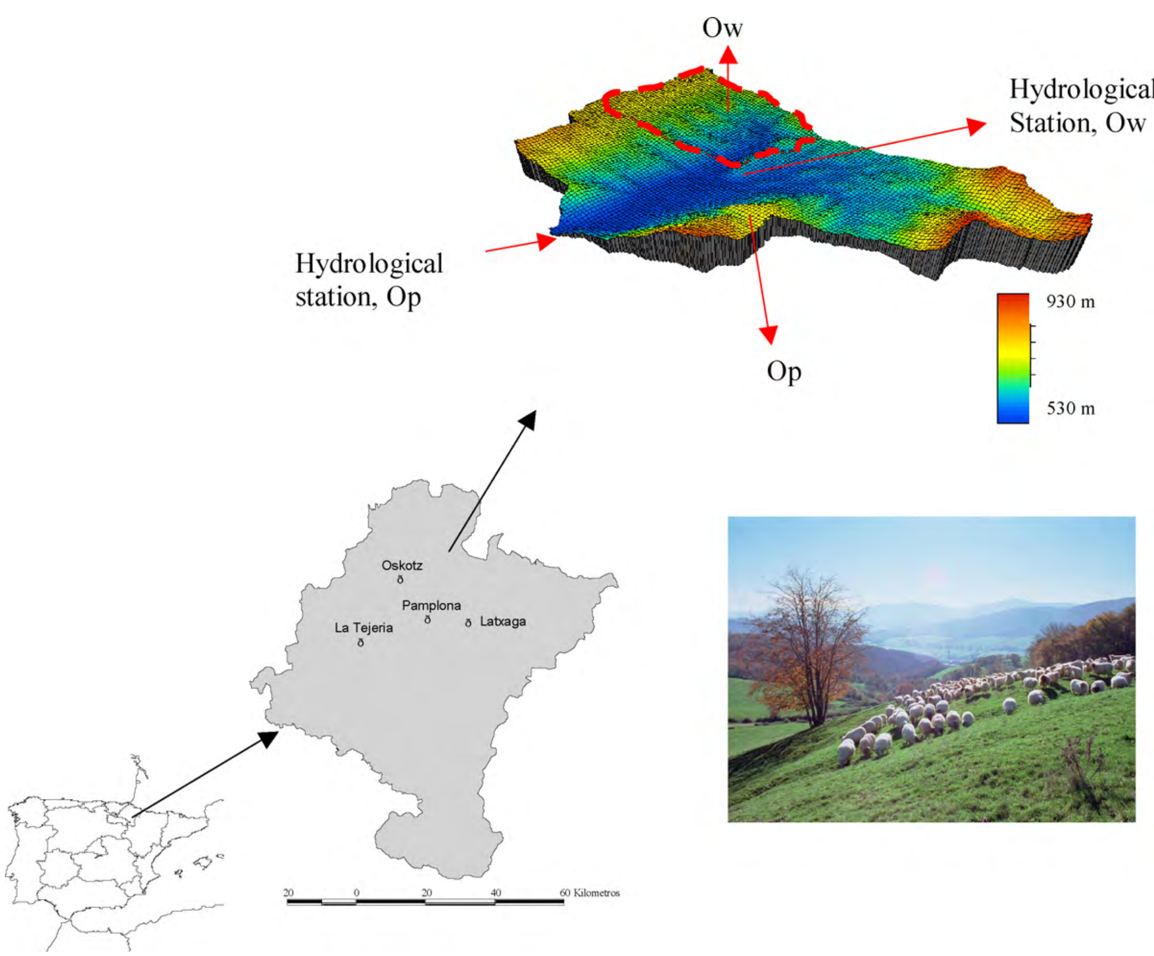

Fig. 1. Oskotz principal, Op, and Oskotz woodland, Ow, watersheds located in Navarre. The grain-sown watersheds named Latxaga and La Tejería (Casalí et al., 2008) are also located in the map. Pictures of Op.

Table 1
Some morphological characteristics of Latxaga and La Tejería (after Casalí et al., 2008) as well as Oskotz watersheds.

	Latxaga	La Tejería	Oskotz
Area (km^2)	2.07	1.69	16.74
Perimeter (km)	6.67	5.46	53.94
Total channel length (km)	5.38	3.20	18.49
Minimum elevation (m)	504	496	530
Maximum elevation (m)	639	649	924
Av. slope (%)	19.3	14.8	20.3
Av. (permanent) channel slope (%)	12.4	14.6	13.8
Gravelius index	1.30	1.17	3.69
Shape factor	0.44	0.85	1.07
Drainage density (km km^{-2})	2.61	1.91	1.10

Table 3
Physical-chemical characteristic of the slurry. Average values.

Parameter	Value	Unit
Density	1020	kg m^{-3}
pH	7.04	–
Electric conductivity	9.72	dS m^{-1}
Dry matter	69.73	kg m^{-3}
Organic matter	71.36	g/100 g dm
Organic matter	4.98	kg m^{-3}
N-total	2.19	kg m^{-3}
N-organic	1.22	kg m^{-3}
N-NH_4	0.97	kg m^{-3}
P_2O_5-P	1.31	kg m^{-3}
K_2O-K	1.45	kg m^{-3}

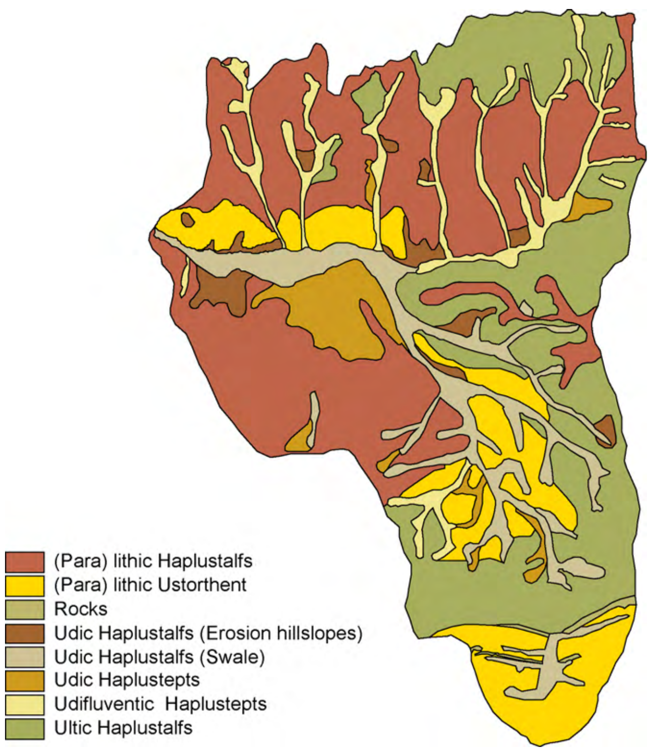

Fig. 2. Soil map (USDA Soil Taxonomy, 2010) of Oskotz.

61%) mainly by *Fagus sylvatica*, *Quercus pyrenaica* and *Pinus* spp., whereas the remaining area is devoted to pasture (653 ha, 39%) with cattle-breeding (ca. 2.3 animal ha^{-1}) and a small part dedicated to cropping.

Grasslands are devoted to animal (cows and sheep) grazing. Pastures are both natural and cultivated. The former occupies the shallower soils and/or the sloping area; these grasses belong to *Lolium*, *Festuca*, *Brachypodium*, *Bromus*, *Trifolium* and *Melilotus* species. Cultivated pastures are normally sown every 4–5 years during autumn, and comprise species such as *Lolium multiflorum*, *Lolium perenne*, *Trifolium pratense* and *Trifolium repens*. They are cut for hay twice a year – in May and June – yielding approximately 10,000 and 14,000 ka ha^{-1}, respectively. The following practices are generally carried out in these grasslands. During autumn, normally around November, fertilization is performed using a P–K–Mg–Z fertilizer at a dose of ca. 450 kg ha^{-1}. Afterwards, animals are allowed to graze until May when nitrogen is applied; this consists of ca. 150 kg ha^{-1} of urea. In April, an additional fertilization is performed using slurry sprinkled over the soil surface at a dose of 100,000 l ha^{-1}, which provides ca. 13 P kg ha^{-1} and 22 N kg ha^{-1} (see Table 3). After the first grass cutting, nitrogen fertilizer or slurry is normally applied again. Moreover, animals are rotated to different pasture sites to avoid overgrazing, and abandoned pieces of land are normally fertilized with urea (100 kg ha^{-1}) or slurry (70,000 l ha^{-1}). It was observed that, occasionally, an excessive application of slurry is coincident with important rainfall and subsequent runoff can produce some water pollution nearby. This can be a problem for the aquatic life (eutrophication) but not a risk for humans since surface water is not used for drinking.

One automatic weather station was installed in the watershed (Fig. 1) (Casalí et al., 2008). Air temperature, rainfall, relative air moisture, wind speed and direction, soil temperature, soil moisture and solar radiation were recorded on a 10 min basis.

Additionally, 2 automatic hydrology stations were installed in the watershed (Fig. 1). The first one named *principal* (Op) monitors the whole watershed (forest and pasture). The second one named *woodland* (Ow) is located at the outlet of a ca. 500-ha sub-watershed almost fully covered with forest – approximately 90% – and pasture. At both hydrology stations the water level and turbidity were also recorded every 10 min. The discharge measurement device consisted of a triangular profile flat-V weir (Bos, 1978). This hydraulic structure was selected, among other reasons, because its design permitted the sediment to pass the control section. Discharge was calculated from water level data, which were monitored using a pressure probe. Water samples were taken every 6 h from a hemispheric hollow, 0.66 m in diameter, made in the downstream face of the triangular profile flat-V weir. For this purpose, an automatic programmable sampler was used, consisting of 24,500-ml bottles. Water samples were analyzed following the standard methods for water quality parameters at the Agricultural Laboratory of the Department of Agriculture and Food of the Government of Navarre. Soil sediment concentration and dissolved nitrate and phosphate

Table 2
Main soil characteristics for Oskotz watershed.

Classification (USDA Soil Taxonomy, 2010)	Geomorphology	Upper horizon texture (USDA)	Area (ha)	Organic matter content (%)	Soil depth (m)
(Para)lithic Ustorthent	Erosion hillslopes	Loam-clay-silty	1437	3.47	1.00
(Para)lithic Haplustalfs	Erosion hillslopes	Loam-clayey		6.41	0.80
Ultic Haplustalfs	Erosion hillsopes	Loam-clayey		5.81	0.80
Udic Haplustalfs	Accumulation hillslopes	Loam-clay-silty	130	6.31	1.35
Udic Haplustepts	Accumulation hillslopes	Loam		2.52	1.20
Udic Haplustalfs	Swale	Loam-clay-silty	107	6.39	1.55
Udifluventic Haplustepts	Swale	Loam-clayey		4.21	1.75

concentrations were determined, as well as other chemicals that are not treated in this paper (i.e. sulphate, carbonate, bicarbonate, potassium, calcium, magnesium and sodium). The four samples collected each day were mixed together prior to analysis to provide a representative daily average sample for determining sediment and nutrient concentrations (Isidoro et al., 2003). In order to characterize the morphology of the watershed (Table 1), two indices (Gravelius index and shape factor) were used.

The Gravelius index, K_c, is defined as (Bendjoudi and Hubert, 2002):

$$K_c = 0.28\frac{P}{A^{0.5}} \tag{1}$$

where P is the watershed perimeter (m) and A is the watershed area (m^2).

A circular watershed has a K_c value close to unity. The longer the watershed, the lower its K_c value.

The shape factor, K_f, is defined as (Monsalve Sáenz, 1999):

$$K_f = \frac{A}{L^2} \tag{2}$$

where L is the maximum length along the main stream from the outlet to the most distant ridge on the drainage divide (m). Watersheds with a low shape factor value (K_f) tend to have sharp peaked flood discharges.

The experimental watersheds named Laxtaga and La Tejería, whose hydrological responses are herein compared to that of Oskotz, are briefly described next (Fig. 1 and Table 1). Both watersheds located in the central western part of Navarre are roughly similar to each other regarding size (approximately 200 ha), geology (marls and sandstones), soils (alkaline, fine texture topsoil), climate (humid sub-Mediterranean) and land use (80–90% cultivated with winter grain crops, mostly wheat and barley). These watersheds were monitored during 10 years (1996–2005) and the corresponding dataset was analyzed in a way similar to that of the Oskotz watershed, presented herein. For more information about Laxtaga and La Tejería watersheds, we refer to the original research paper (Casalí et al., 2008), where they are described in detail.

3. Data analysis and discussion

3.1. Rainfall and runoff

We will assume that Oskotz principal (Op) and Oskotz woodland (Ow) share the same type of rainfall, i.e. amount, intensity and duration, typical of a (sub-)Atlantic climate. In general, the inter-annual variability of the precipitation in these watersheds was high, with the maximum variation observed in autumn and the minimum in summer (Table 4 and Fig. 3). The accumulated annual rainfall ranged from 1135 mm (agricultural year 2006–2007) to 770 mm (agricultural year 2001–2002) with an average value of 1206 mm (Table 4 and Fig. 3). Additionally, the rainfall showed a slight seasonal pattern: autumn and winter were the wettest period, whereas summer was usually the driest (Table 4 and Fig. 3). However, the precipitation was still important in this last season with approximately 13% of the annual precipitation.

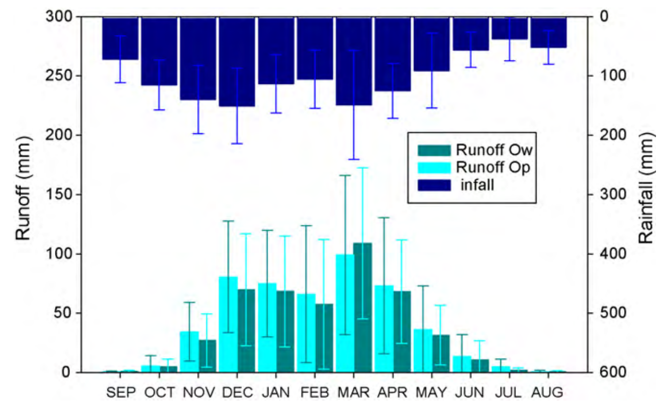

Fig. 3. Monthly average rainfall and runoff at Oskotz. Vertical bars area standard deviation.

Nevertheless, and according to the EI_{30} rainfall erosivity index (Morgan, 2005) (EI_{30} is a compound index of kinetic energy of the rain, E, and the maximum 30-min intensity, I_{30}) determined for around 850 precipitation events occurred during the whole recorded period (not shown) reveals that more than 70% of the rain events had a (very) low erosivity ($EI_{30} < 100\ \mathrm{MJ\,mm\,m^{-2}\,h^{-1}}$) (Fig. 4). In contrast, just a few rain events mainly occurring during summer had (very) high erosivity, i.e. 2 or 3 orders of magnitude higher than the above. On the other hand, it is known that rain falling with a relatively low intensity can be collected on the leaves of a forest canopy and then drip from the leaves in large drops (leaf drainage). Also, from a height of 10 m or so these drops will reach their terminal velocity (Selby, 2005). Since some predominant tree species in Ow, e.g. *F. sylvatica*, are more than 20 m in height, the overall splash erosion risk in Ow is to some extent greater than that in Op; this erosion risk is even higher for *F. sylvatica* due to the scant understorey vegetation that this tree allows to grow during summer. Nevertheless, we shall make no distinction between the rainfall erosivity inside and outside the forest area.

As regards runoff, there are slight differences between Op and Ow (Table 4 and Fig. 3). In general, the seasonal runoff patterns were more pronounced than those of the precipitation, with an average

Table 4
Some characteristics of precipitation and discharge data recorded at Oskotz.

	Accumulated precipitation (mm)		Accumulated discharge (mm)		Runoff coefficient (%)	
	Mean	σ	Mean	σ	Mean	σ
Oskotz woodland						
Autumn	405	128	102	64	22	11
Winter	367	88	225	101	59	22
Spring	272	98	111	76	38	18
Summer	161	46	4	3	2	2
Annual	1206	131	441	120	36	8
Oskotz principal						
Autumn	405	128	121	63	28	8
Winter	367	88	215	102	58	24
Spring	272	98	123	103	40	22
Summer	161	46	6	7	4	3
Annual	1206	131	465	137	38	8

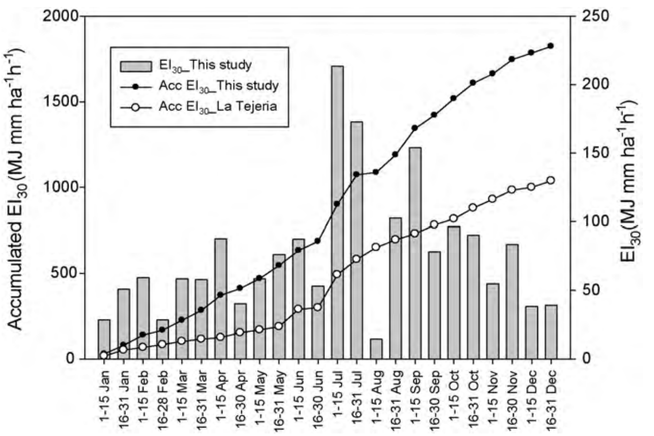

Fig. 4. Average fortnightly (bars) and accumulated average fortnightly (line) values of rainfall erosivity (EI_{30}) at Oskotz (average values for the period studied). Accumulated average fortnightly values of EI_{30} for La Tejeria (after Casalí et al., 2008) is also shown for comparison. Criteria for assessing rainfall events: (i) a precipitation must accumulate a minimum of 0.2 mm to compute as a rainfall event; (ii) more than 6 h from the last rainfall event must pass before computing a new event; (iii) rainfalls spanning more than 1 day were considered separate events because the temporal resolution of the rainfall data was the calendar day.

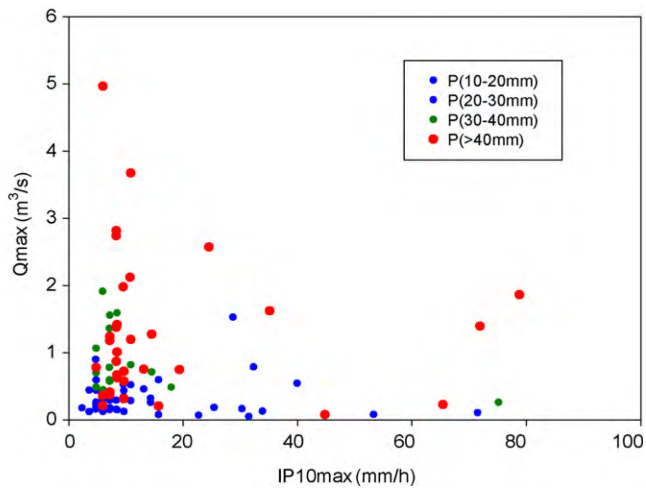

Fig. 5. Relationships between maximum rainfall intensity in 10 min $IP_{10\ max}$ and the corresponding peak flows Q_{max} for individual rainstorm events P.

discharge one order of magnitude larger in winter (Op: 215 mm; Ow: 225 mm) than in summer (Op: 6 mm; Ow: 4). Furthermore, almost 60% of the precipitation turned into runoff in both sites during winter, whereas in summer it was only 4% and 2% in Op and Ow, respectively (Table 4). The large relative difference (approximately 50%) between Ow and Op in the water yield recorded in summer may be to some extent explained as follows. During summer, vegetation favoured canopy interception and evapotranspiration. But, evapotranspiration of trees (and hence in Ow) exceeds that of shrubland and grassland (therefore, in Op) (Gallart and Llorens, 2004; Guojing et al., 2005; Zhang et al., 2001) thus leading to a smaller runoff response in Ow than in Op. This reduction in runoff in forest area is also to some extent explained by for both the high infiltration rate due to the soil macro-porosity and the drier antecedent conditions of soils before any event (Gallart and Llorens, 2003). For example, a 10% reduction in the cover of deciduous hardwood gave between 17 and 19 mm (Sahin and Hall, 1996) and 25 mm (Bosch and Hewlett, 1982) increase in water yield. In contrast, in autumn and winter and due to an increase in both accumulated precipitation and soil moisture content, the discharges rose accordingly in both sites. However, the increase in discharge is more proportional than that of precipitation; the reason for that could be to some extent explained analyzing Fig. 5. This figure shows the relationships between maximum rainfall intensity in 10 min and peak flow for more than 100 different rainfall events (between 2001 and 2008). The lack of any trend in the results suggests that the intensity and volume of rainfall events do not alone explain the hydrological response of the catchments. It is then believed that the antecedent rainfall or soil moisture contents play a key role in the increment in runoff depth (Serrano-Muela et al., 2008).

On the other hand, Latxaga and La Tejería watersheds presented roughly similar patterns of rainfall and runoff to those for Oskotz – Ow/Op – (cf. Casalí et al., 2008). However, in the latter watershed, the average annual rainfall and runoff coefficient are respectively ca. 40% and 60% larger than those recorded in the grain-sown watersheds (Fig. 6A). This is not surprising considering the more humid type of climate of Oskotz (sub-Atlantic) compared with that of Latxaga and La Tejeria (humid Mediterranean climate). Besides, and more relevant for our comparison, the total erosivity power of the rainfall in Oskotz is roughly double than that in the grain-sown watersheds. Additionally, most of the erosive rainfalls in Oskotz occur during summer (Fig. 4) as is also the case for the grain-sown watersheds (cf. Casalí et al., 2008).

3.2. Sediment concentration and yield

The annual sediment yield and the average sediment concentration were higher at Ow than at Op (Table 5 and Fig. 7). In disagreement with our findings, some authors have reported a pastured catchment having exported notably more sediment (ca. 2.5 t ha^{-1} $year^{-1}$) than a forest/woodland catchment (ca. 1 t ha^{-1} $year^{-1}$) (Neil and Fogarty, 1991; Mahmoudzadeh et al., 2002). Erskine et al. (2002) reported a similar amount of sediment exports between grazed pasture and forest basins, although these authors attribute this similarity to the fact that the forest basins were also grazed. Nevertheless, it is widely recognized that dense forests and grass provide the best soil protection and are about equal in effectiveness (Brady and Weil, 2008). However, this assumption is indeed fully applicable when considering woodland with a dense understorey (Wischmeier and Smith, 1978) which is not the case in Oskotz especially during summer time as mentioned above, though a leaf litter is present most of the time protecting the soil. Also, the regular clearance of part of the forest biomass accounted to a great extent for the larger sediment yield at Ow than that at Op, although the latter is also – but partially – occupied by forest. Moreover, logging, especially when occurring in sloping areas, may trigger soil erosion processes in unprotected soils. In addition, one of the main erosion problems in logged areas is associated with skid trails and roads, which are frequently areas of bare compacted soils (Clarke and Walsh, 2006). This was the case at Ow, and even at Op in 2003, when the erosion rate, and hence, sediment production, rocketed soon after a tree clearance (see Fig. 7).

However, sediment yield recorded at Op and Ow corresponded to much lower erosion rates than average figures for agricultural fields in Spain (López Bermúdez and García Ruiz, 2008), and even below critical thresholds of soil loss tolerance (Schertz, 1983). Likewise, sediment concentration was normally below a critical threshold of 1000 mg l^{-1} proposed by Bodí and Cerdá (2008) for eroded hillslopes; they relate the sediment concentration ratio to the erodability of the soils.

On the other hand, both sediment concentration and sediment yield at Op and Ow presented a large inter-annual variability, which is normal as they are mainly controlled by rainfall events. Maximum and minimum values of sediment yield at Op and Ow were 1487–143 and 1226–210 t ha^{-1} $year^{-1}$, respectively, whereas for

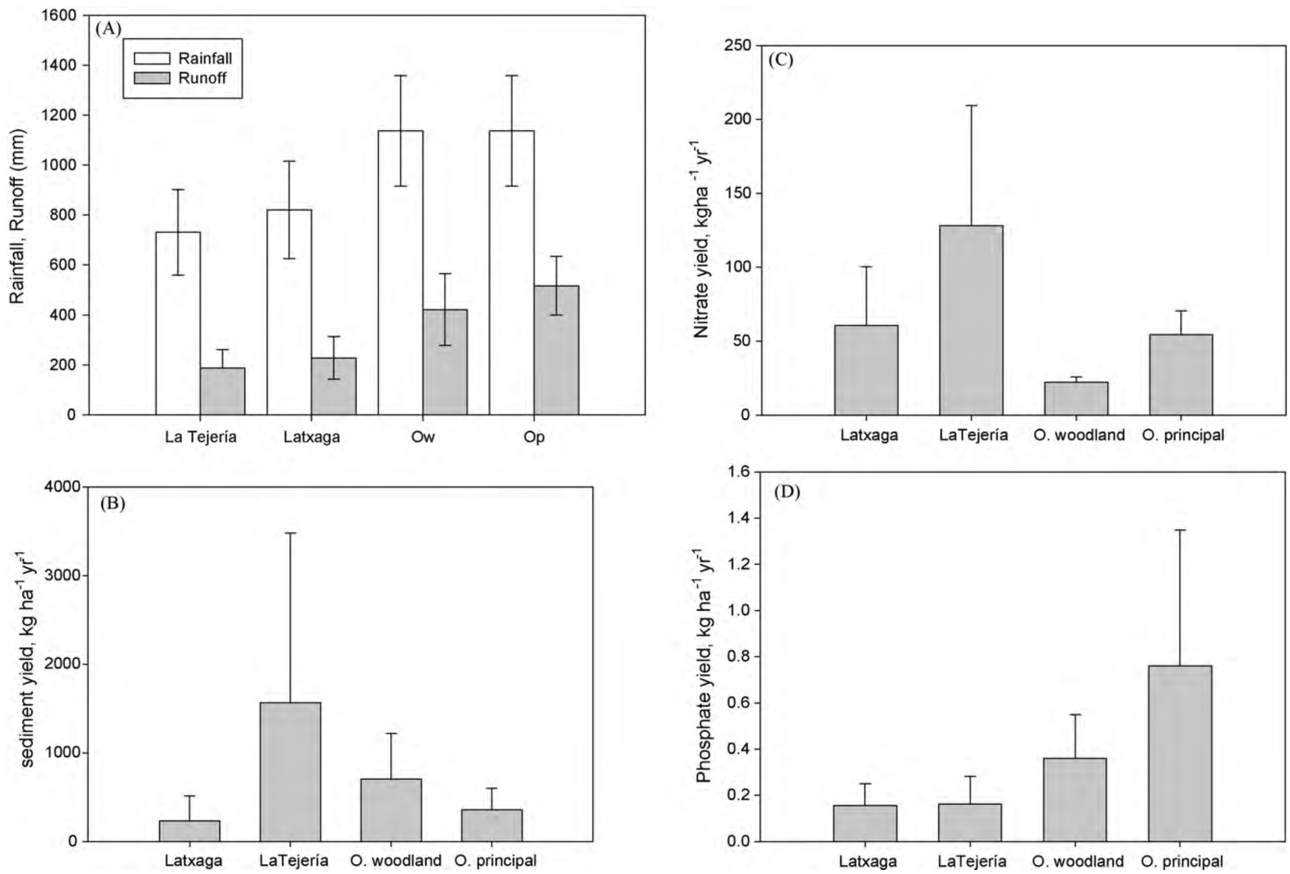

Fig. 6. Annual average (A) rainfall, runoff, (B) sediment yield, (C) nitrate, and (D) phosphate yield values at La Tejería and Latxaga (after Casalí et al., 2008) and Oskotz watersheds. Nitrate/phosphate ratios are always referred to the total area of the catchment; since the nitrate/phosphate yields at Op come mostly from the pastured area, the corresponding nitrate/phosphate ratio is somewhat underestimated.

daily sediment concentration they were 45–30 and 103–28 mg l^{-1}, respectively (Table 5). Furthermore, it is remarkable that most of the annual sediment yields at Op and Ow were a result of just a few precipitation events. This is in agreement with previous quantitative and qualitative (Donézar et al., 1990a,b) estimations of soil erosion made for Navarre.

Unlike sediment concentration, sediment yield showed a clear seasonal pattern (Fig. 8). More precisely, sediment yield largely occurred during winter and beginning of spring (Fig. 8), when, however, as mentioned above, most of the rainfall had a low erosivity power. The most likely explanation for this is twofold. On the one hand, during winter, soils under the forest are highly vulnerable to the raindrop impact since the plant canopy is scant during this period of the year (deciduous trees) despite the fact that canopy protection is to some extent substituted by plant residue litter. Similarly, when the grass is dormant, i.e. late autumn through early

Table 5
Annual values of sediment, nitrate and phosphorus yield, their average values, and the average concentrations of these parameters for the whole studied period.

	Sediment		Nitrate		Phosphate	
	Conc. (mg $^{-1}$)	Yield (kg ha^{-1} year^{-1})	Conc. (mg l^{-1})	Yield (kg ha^{-1} year^{-1})	Conc. (mg l^{-1})	Yield (kg ha^{-1} year^{-1})
Oskotz woodland						
2002/2003	103	1487	16	24	0.44	0.72
2003/2004	65	143	18	27	0.21	0.34
2004/2005	31	266	14	22	0.20	0.37
2005/2006	85	1088	17	24	0.13	0.25
2006/2007	73	771	9	18	0.07	0.17
2007/2008	28	481	8	18	0.11	0.31
Average	64 (30)	706 (514)	14 (4)	22 (3)	0.19 (0.13)	0.36 (0.19)
Oskotz principal						
2002/2003	45	774	31	56	0.60	1.75
2003/2004	46	210	38	58	0.57	0.94
2004/2005	57	357	29	53	0.60	0.96
2005/2006	63	1226	54	77	0.53	0.12
2006/2007	51	365	30	56	0.13	0.34
2007/2008	30	424	13	27	0.20	0.45
Average	49 (12)	559 (376)	33 (13)	54 (16)	0.44 (0.21)	0.76 (0.59)

Standard deviation is shown in parentheses.

spring, soil protection by the pasture cover is less effective than during the rest of the year. On the other hand, during winter the soils in the whole watershed are almost saturated leading to large runoff rates (Table 4) flowing over more vulnerable soils. Additionally, when the soil is wet, the cattle can damage the pastures by trampling and compacting the softened sod, destroying soil structure and reducing infiltration and vegetative cover as well. For instance, Owens et al. (1997) reported from a small pastured watershed a strong increment in sediment losses resulting from winter grazing. Therefore, sediment yield at Oskotz could be explained mainly by the vegetation and soil conditions rather than by the erosivity of the rain.

With regard to sediment concentration, it can be seen that there is no systematic variation pattern of it throughout the year; it is relatively large even with a scant total runoff (Fig. 8). In association with this last finding, Mateos and Giráldez (2005) demonstrated that soil erosion rates, and, consequently, suspended sediment, can be high even due to the action of small runoffs flowing over very gentle terrains.

On the other hand, sediment yield at Oskotz was clearly linear-regressed with total discharge both for a single rain event (Fig. 9) and even for a monthly average (graph not shown, $R^2 = 0.75$). This is not a common fact since, normally, successive rain events transport less sediment than the prior rain events because the available sediment is changing depending on the antecedent rain history (Beschta, 1978; Nistor and Church, 2005). This observation suggests that Oskotz responds to a transport-limited system rather than a weathering or supplied-limited one (Carson and Kirkby, 1972). In a transport-limited watershed more sediment is generated in upland areas than the stream channels can transport (Keller et al., 1997). This finding is also in agreement with the fact that, as mentioned above, a large sediment concentration at Oskotz was recorded even at small discharges. Brardinoni et al. (2003) stated that small (not visible from aerial photographs) landslides – most

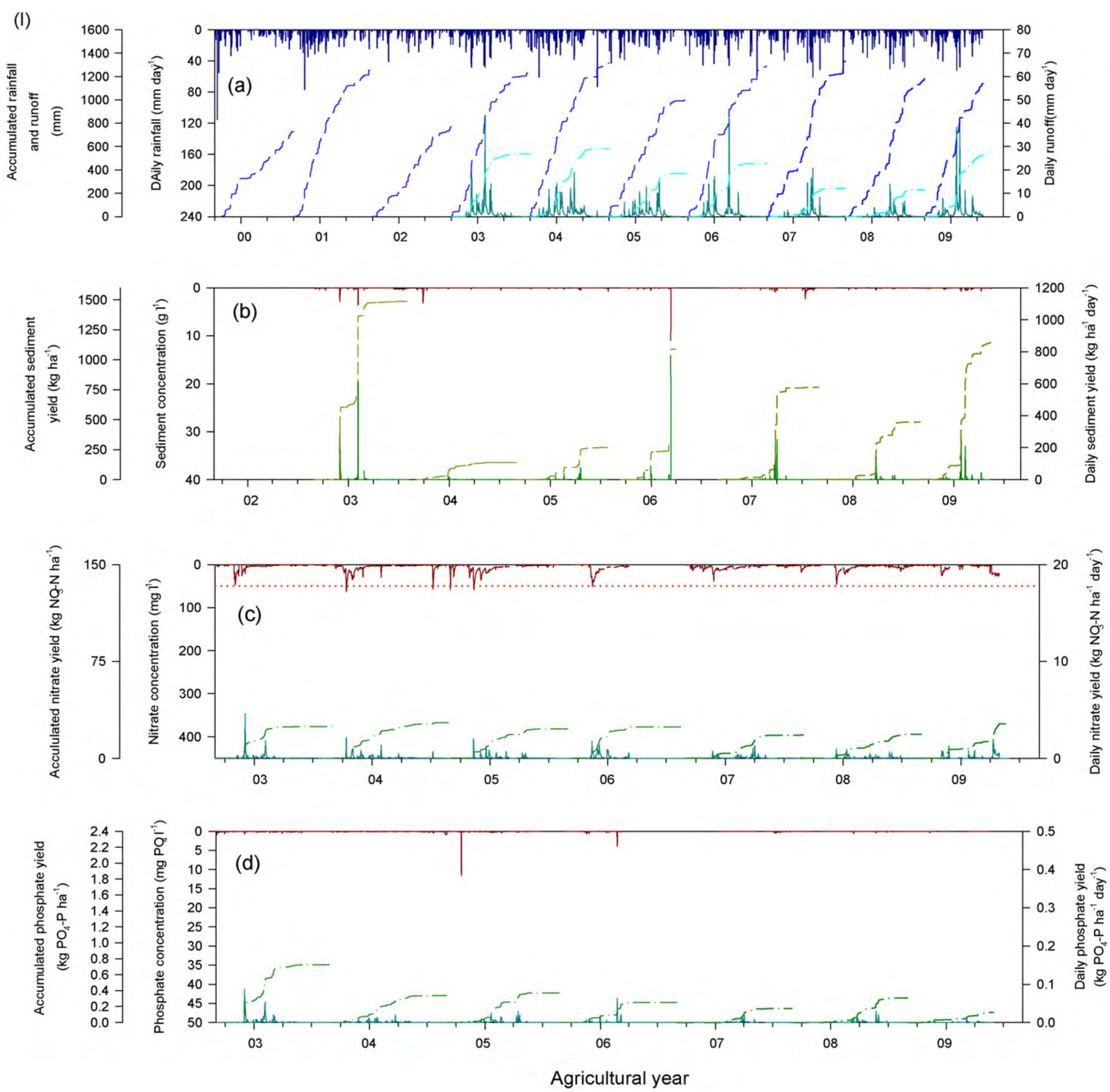

Fig. 7. Results of (A) rainfall and runoffs data, (B) sediment, (C) nitrate and (D) phosphate concentrations and yields recorded at (I) Oskotz woodland and (II) Oskotz principal.

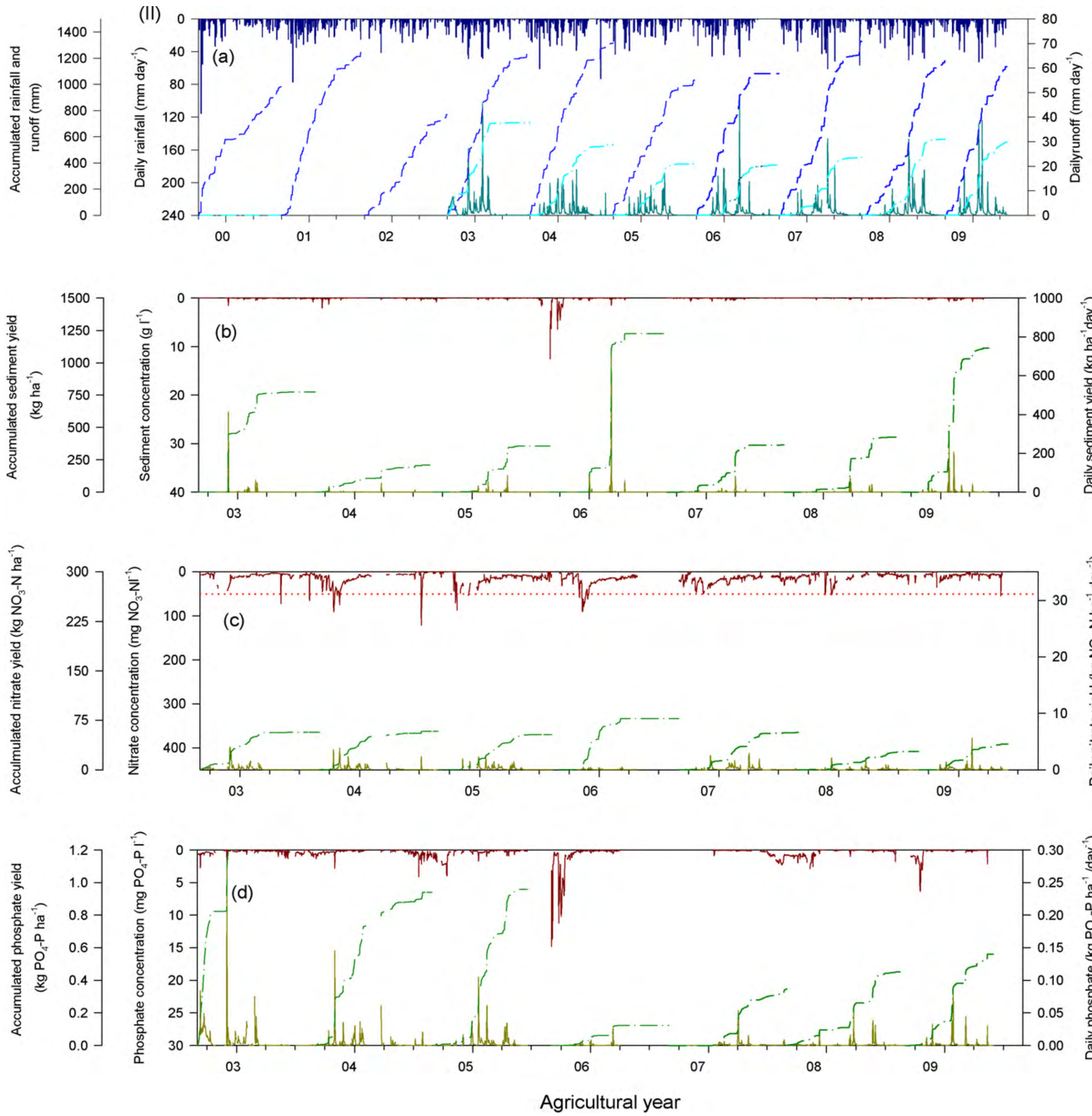

Fig. 7. (*Continued*).

of them connected to the drainage network – present in a rugged forested watershed were responsible for an important extra supply of material to the basin drainage system. The authors suggested that this additional supply defined the transport-limited behaviour of the basin; in other basins, where these failures were negligible, the system was, on the contrary, of a supply-limited type. From our field observation we believe that at Oskotz the extra sediment supply comes from the non-consolidated roads or paths existing throughout the woods. Despite the fact that these roads occupied an insignificant percentage of the total watershed area, throughout the year they are an important source of soil prone to be eroded by runoff. In La Tejería and Laxtaga watersheds, however, factors influencing erosion – protection afforded by crops, soil tillage, etc. – can dramatically change not only throughout the year but also within the catchment. As a consequence, it is not surprising that sediment yields for the grain-sown watersheds are poorly regressed with total discharge (not shown).

A comparison between the average sediment yield in Oskotz with those at Laxtaga and La Tejería reveals an interesting issue. First of all, it is important to point out that the Oskotz watershed possesses some much more pronounced natural and critical characteristics, and, hence, these are more likely to promote a larger erosion rate than those at Laxtaga, i.e. vast areas of extremely steep terrain (up to 65%), a large amount of rainfall during the year, and a larger number of (highly) erosive events. Despite all these facts, differences in average sediment yield at Op and Laxtaga watersheds are quite small (Fig. 6B). This suggests that the forest/pasture cover in Oskotz offsets, to some extent, the more favourable natural conditions of soil erosion occurring in this watershed compared with those conditions prevailing in the grain-sown watershed of Laxtaga. The effect of the different land use (i.e. forest/pasture vs. winter cereal) is even more evident when observing the average sediment yield at La Tejería: it is almost double than that at Laxtaga and Oskotz (Fig. 6B). The more circular shape of La Tejería watershed

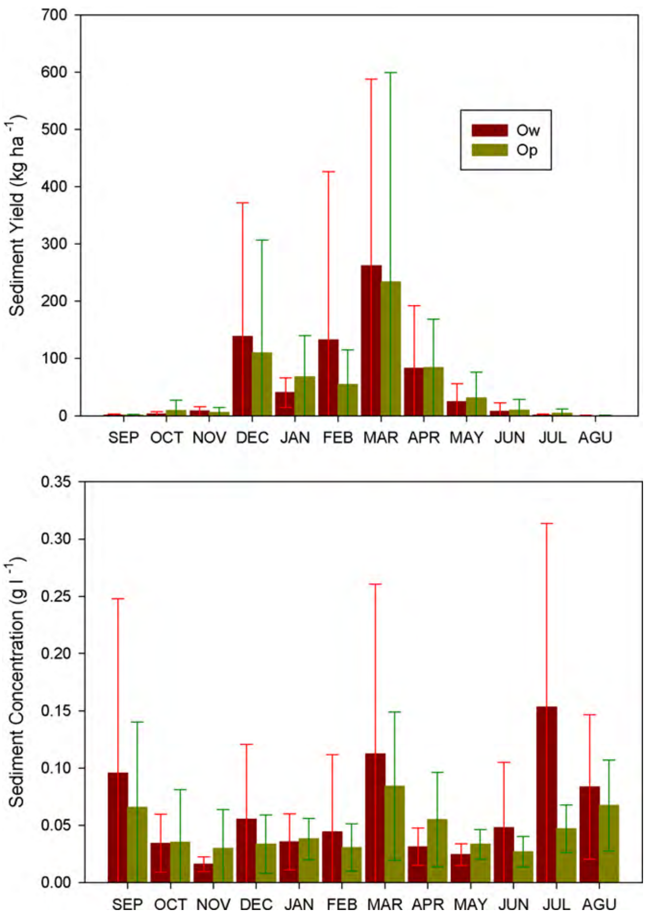

Fig. 8. Monthly average sediment yields and sediment concentration at Oskotz watershed.

compared with that of Laxtaga, along with its smoother topography and higher slope gradient of the stream channels, mainly affords a more efficient removal of water and sediment (Casalí et al., 2008). However, these are, as a whole, in our opinion, small unfavourable natural conditions compared with those prevailing at Oskotz. This suggests that, as far as soil erosion is concerned, our watersheds cultivated with winter grain crops are very sensitive to the prevailing morphological and topographical characteristics. Generally, in Spain, cereal crop has been traditionally associated with high erosion rates even in gentle sloping areas (López Bermúdez and García Ruiz, 2008). Moreover, under this land use, the soil surface remains uncovered during long periods of time corresponding to the soil preparation and crop establishment phases, which frequently occur during the wettest seasons. Besides, soils under cereals are much more vulnerable to the erosion power of extreme rainfall events as illustrated, for example, in the works by Bienes et al. (1996), De Alba (1998) and Casalí et al. (2008).

3.3. Nitrate and phosphate in water courses

The average nitrate/nitrogen yield exported at Op (54/12 kg ha^{-1} year^{-1}) was double than that recorded at Ow (22/5 kg ha^{-1} year^{-1}), and similar differences were verified in nitrate concentration (Table 5 and Figs. 7 and 10). These differences are not surprising considering that land use and land cover types influence nitrogen export (Hillel, 1998; Álvarez-Cobelas et al., 2008). Overall, forest in catchments limits soil nitrogen delivery to streams (Vanderbilt et al., 2003) mainly due to the relatively high denitrification potential of their soils (Hayakawa et al., 2006). However, there are some differences in nitrogen export depending on the type (Lovett et al., 2000; Compton et al., 2003) and maturity of the forests (Emmett, 1993). Moreover, watersheds dominated by pasture export normally twice more total nitrogen than those dominated by forest (Álvarez-Cobelas et al., 2008). A worldwide analysis revealed that the total average nitrogen exported from watersheds dominated by deciduous forest was ca. 9 kg ha^{-1} year^{-1} and up to a maximum of ca. 28 kg ha^{-1} year^{-1}

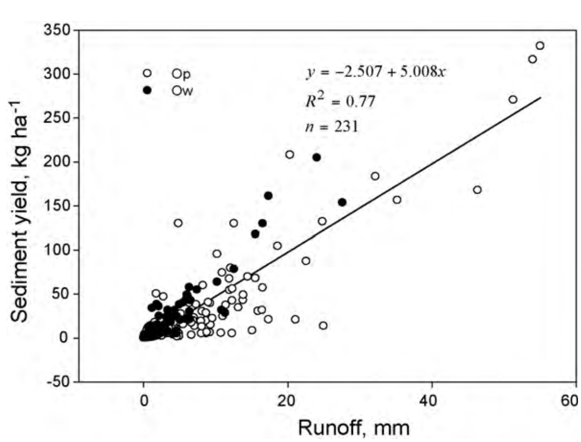

Fig. 9. Sediment yield vs. runoff for single events at Oskotz. Criteria for assessing rainfall events: (i) a precipitation must accumulate a minimum of 0.2 mm to compute as a rainfall event; (ii) more than 6 h from the last rainfall event must pass before computing a new event; (iii) rainfalls spanning more than 1 day were considered separate events because the temporal resolution of the rainfall data was the calendar day.

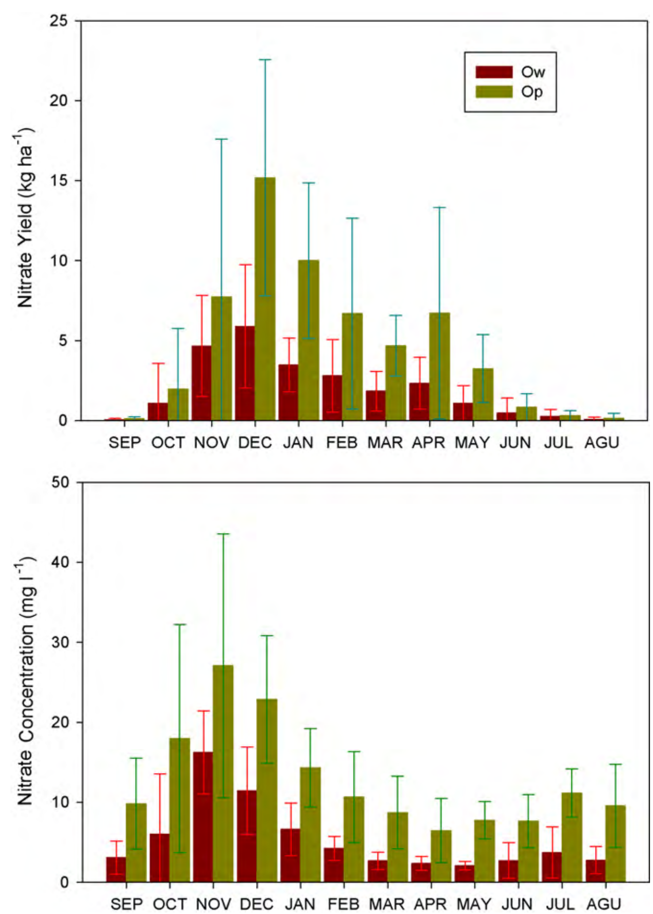

Fig. 10. Monthly average nitrate yield and concentration at Oskotz watershed.

(Álvarez-Cobelas et al., 2008). However, for watersheds dominated by pastures, these amounts were slightly lower than those for forest watersheds: ca. 7 and 20 kg ha^{-1} year^{-1}, respectively. Similarly, nitrate outputs in stream water of 24 forest watersheds in the northeastern United States ranged from 0.1 to 5.7 kg ha^{-1} year^{-1} (Campbell et al., 2004). Furthermore, Frink (1991) carried out an extensive literature review about N and P (for P survey, see below) export from large watersheds with different land uses, also in the northeastern United States. This literature survey showed an average nitrogen export of approximately 2.5 kg ha^{-1} year^{-1} and up to ca. 8 kg ha^{-1} year^{-1} from a large number of forested watersheds, whereas, for pastureland, average and maximum values rose to ca. 3.5 and 15 kg ha^{-1} year^{-1}. So, it appears that nitrate yield exported at Oskotz (Op and Ow) is rather at the upper end of that reported in watersheds in other parts of the world.

A relatively high leaching loss of NO_3-N is considered to be a sign that N inputs exceed the biological demand for N. Data from European watersheds showed that with N inputs of less than 10 kg N ha^{-1} year^{-1}, nearly all the N was retained, while most of the significant N leaching was found at watersheds receiving inputs greater than 25 kg ha^{-1} year^{-1} (Campbell et al., 2004). It is believed that fertilizer applications on Op largely account for the differences in nitrate in the stream water at Op compared with that at Ow (Fig. 7). Nitrogen fertilization (only urea, not considering the nitrogen from slurry) at Op is greater than 100 kg N ha^{-1} year^{-1} (see above). However, nitrate concentrations, even at Op, rarely exceed the critical level of 50 mg NO_3 l^{-1} for drinking water (EC, 1991; Fig. 7).

On the other hand, nitrate yield and concentration showed a clear seasonal pattern in both sites with the highest amount occurring during winter and early spring (Fig. 10). This is mainly explained by the lower plant uptake and microbial immobilization during the winter period leaving nitrate available to leach (Foster et al., 1989; Bruland et al., 2008). Consequently, the relationship between runoff discharge and N export is typically stronger during the dormant season when biotic retention of N is lower (Campbell et al., 2004): compare Fig. 3 with Fig. 10.

Like nitrate, phosphate/phosphorus yield and phosphate concentration recorded at Op (0.76/0.25 kg ha^{-1} year^{-1}, 0.44 mg l^{-1}) were twice as high as those at Ow (0.36/0.12 kg ha^{-1} year^{-1}, 0.19 mg l^{-1}) (Table 5 and Figs. 7 and 11). Frink (1991) (see above) for forested watersheds reported average and maximum phosphorus export values of around 0.12 and 0.9 kg ha^{-1} year^{-1}; while, for pastured watersheds, average and maximum values were ca. 0.5 and 3 kg ha^{-1} year^{-1}. Similarly, Dillon and Kirchner (1975) reported annual average phosphorus export for a large number of watersheds with contrasting geology in Southern Ontario. For forested watersheds, average phosphorus value was ca. 0.1 kg ha^{-1} year^{-1}, whereas from those with forest and pasture this average value rose to 0.3 kg ha^{-1} year^{-1}. It therefore appears that the P exported at Oskotz corresponds to common values reported in the literature.

At both sites, these exported P values corresponded to water with a significant eutrophication risk (EEA, 1999). To be more precise, the critical levels of phosphorus in water, in which eutrophication is likely to be triggered, are approximately 0.03 mg l^{-1} (Brady and Weil, 2008). Within Ow, phosphorus losses coming from fertilization of the small area devoted to pasture and agriculture (ca. 15% of the total area) are assumed to be minimal and so it is negligible. On the other hand, at Op, animal waste left unincorporated on the surface of pastures facilitated losses of phosphorus dissolved in the runoff water. In fact, large amounts of dissolved P can potentially be leached from the manure after a few rainfall events (Sharpley and Moyer, 2000), thus travelling preferentially with direct runoff. In addition, surface application of animal waste without incorporation resulted in an increment in phosphorus concentration in a relatively small volume of runoff water. This P in surplus largely explains why Fig. 11 depicting phosphate concentration throughout the year at Op is a kind of mirror image of Fig. 3 depicting changes of runoff during the year; i.e. the lowest P concentrations are recorded in winter, when the water yield (hence dilution) is the highest. In contrast, no clear seasonal pattern of phosphate concentration was evidenced at Ow (Fig. 11).

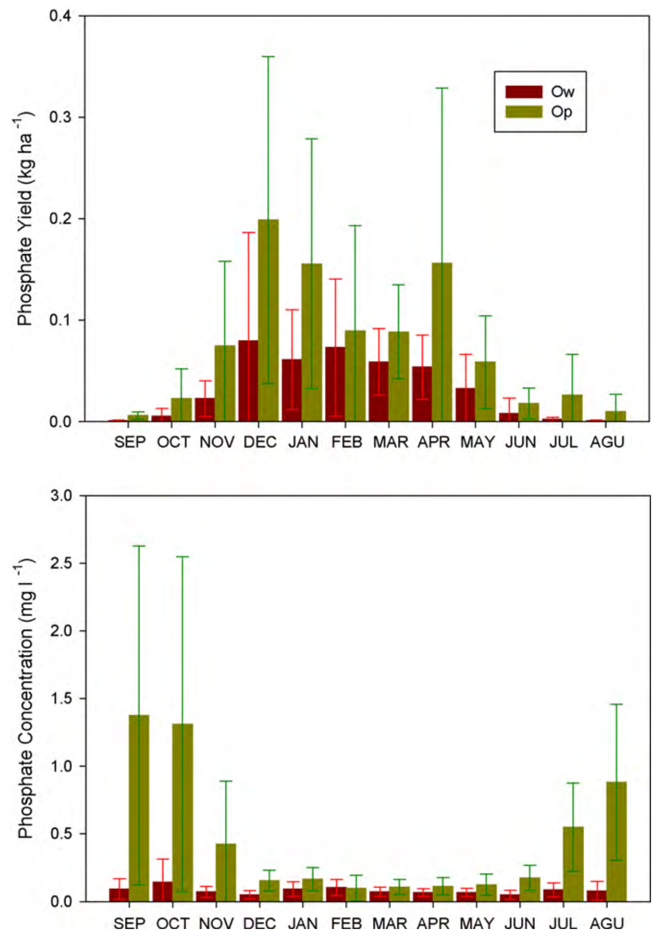

Fig. 11. Monthly average phosphate yields and concentrations at Oskotz watershed.

The comparison between the nitrate yield at Oskotz with that at La Tejería and Laxtaga (cf. Casalí et al., 2008) showed expected results. Total average nitrate yield was the highest in the grain-sown watersheds and the lowest at Ow, which had received no fertilization (Fig. 6C). Agricultural land use within watersheds has precisely been widely linked to an increased concentration of inorganic N in drainage waters (Woli et al., 2002; Hayakawa et al., 2006). This is because (heavy) nitrogen fertilization of crops (especially some grain crops) can be a major source of excessive nitrate since the crops usually take up only a portion of the nitrogen applied (Brady and Weil, 2008). Besides, the nitrate yield variability also appears to increase with the application of fertilizer and so it is smaller at Ow (Fig. 6C).

Unlike nitrate, phosphate yield at Oskotz is much higher than that at the grain-sown watersheds (Fig. 6D); and this occurs even at the pristine (=fertilizer free) Ow. The reason for that yield is, therefore, not related to an excessive fertilization. Furthermore, as exported P at Ow is largely associated with eroded suspended sediment (see above) and erosion rate in this forested site is lower than in the grain-sown watersheds (at least compared with La Tejería), the dominant factor in the loss of phosphate in runoff appears to be a matter of soil conditions. More precisely, the predominant alkaline soil conditions (pH > 8) in the grain-sown watersheds promote

P fixation in relatively unavailable compounds (Tisdale and Nelson, 1966). This is an alarming issue because P values at the grain-sown watersheds already corresponded to water with a significant eutrophication risk (Casalí et al., 2008), not to mention those at Oskotz, where, on the contrary, the phosphorus is not fixed by the soil.

4. Conclusions

This article presents the second series of results of an unprecedented study in Navarre (Spain) referring to hydrological behaviour – i.e. runoff, sediment yield and water quality – of an experimental watershed under forest and pasture (Oskotz principal), which also possesses a sub-watershed almost exclusively under forest (Oskotz woodland) both representative of wide areas of Navarre and northern Spain. The behaviour of these watersheds contrasts with that of the grain-sown watersheds previously analyzed in Casalí et al. (2008).

In agreement with the current climate characteristics, an important inter-annual variability of sediment and pollutant yields was observed in the forested/pastured watersheds. Furthermore, the sediment yields followed roughly the same seasonal pattern as that of the precipitation and runoff, though these sediment yields were more related to current soil conditions and to the erosive capacity of few, infrequent and (highly) erosive rain events, also typical of the current climate. Generally, all these findings are similar to those observed in the cultivated watersheds; however, there are on average a larger total rainfall/runoff and more frequent erosive rainfalls in Oskotz than in the cultivated watersheds.

The pastures afford a greater protection against soil erosion than the forest, and the latter greater than the crops (cereals). However, the forest's protection, although patent, is lesser than expected due to logging practices, which can trigger major increases in sediment yield at the outlet of the watershed given that they leave part of the soil's surface bare and compacted. However, the relative infrequency with which this logging is carried out – every five years or so – makes its long term harmful effect go unperceived in its real magnitude. In short, the presence of woodlands under our conditions is not a guarantee *per se* of the protection of the soils against erosion. Also, for a correct hydrological characterization of these watersheds, the need to obtain extensive (decades) and continuous hydrological records has been confirmed. This would monitor not only the possible occurrence of natural processes, but also occasional, but unnoticed, human actions.

On the other hand, the nitrate levels recorded in Oskotz, unlike those observed in grain-sown watersheds, are below the thresholds permitted. However, and differently from what was thought *a priori*, the phosphate values in Oskotz, even in the forested sub-watershed, were notably higher than those recorded in the cultivated watersheds. This was due to the intensive cattle-breeding activity (contribution of animal waste) and to the predominant type of soil favouring the mobilization of the phosphorus, unlike what happened in the cultivated watersheds with a predominance of calcareous soils. The implications of this problem are serious; we refer to the degradation of ecosystems, especially aquatic ones, adjacent to the pollution sources.

This study, together with the previous one (Casalí et al., 2008), aims only to be a first, although important, step towards a better knowledge of the hydrological behaviour of our watersheds, and, specifically, the important role they play in the different land uses in sediment yield and water quality, with the ultimate objective of assessing the impact of agricultural activity on our environment.

These works, at first sight basic and descriptive, are, however, indispensable for guiding future research attempting to dilucidate the complex processes involved in the phenomena previously observed and monitored.

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