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Effects of the sequence wildfire-clearcutting-thinning on nutrient export via streamflow in a small *E. globulus* watershed in Galicia (NW Spain)

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Abstract

Water yield and nutrient exports via streamflow were monitorized for twelve years (1987-1999) in a small experimental *E. globulus* watershed subjected to intensive forest management in the NW of Spain. During the period of study the watershed was severely affected by a wildfire and this gave the opportunity to evaluate the influence of this perturbation and the subsequent clearcutting and thinning, on the nutrient exports via streamflow.

The wildfire caused a significant increase in nutrient exports in streamflow during the first two following years while no significant effect was observed the third year after wildfire. After clearfelling, inputs via precipitation compensated for nutrient exports in streamflow, except for K the first year following harvest and NO_3^- during the three years after this operation. Thinning had less effect on nutrient exports than wildfire or harvest.

Increased nutrient concentrations in streamflow and imbalances did not last in time, although dissolved nutrient losses measured in this study threaten forest sustainability in these plantations in intensively managed plantations growing in low fertility soils. Consequently, wildfire being the triggering perturbation for subsequent nutrient loss, fire preventive actions are critical for the sustainability of these stands.

Key words: forest fire; clearcutting; solute loss; atmospheric input.

Resumen

Efectos de la secuencia incendio-corta a hecho-selección de brotes en la pérdida de nutrientes por escorrentía en una cuenca experimental de *E. globulus* en Galicia (NW de España)

La producción de agua y la salida de nutrientes por escorrentía fueron monitorizadas durante doce años (1987-1999) en una pequeña cuenca experimental de *E. globulus* en el NW de España. Durante el período de estudio la cuenca fue afectada por un incendio, lo que brindó la oportunidad de evaluar la influencia de esa perturbación y la corta a hecho y selección de brotes subsigueinte, sobre la salida de nutrientes por escorrentía.

El incendio causó un aumento significativo de las pérdidas de nutrientes por escorrentía durante los dos años siguientes mientras que no fue apreciable ningún efecto al tercer año del incendio. Después de la corta a hecho del arbolado quemado, las entradas por precipitación compensaron las pérdidas por escorrentía, a excepción del K el primer año después de esta operación y del NO_3^- durante los tres años siguientes. La selección de brotes tuvo un efecto mucho menor en las pérdidas de nutrientes por escorrentía que el incendio o la corta.

Los aumentos de las concentraciones y las desviaciones en los balances de nutrientes no fueron duraderos en el tiempo, sin embargo las pérdidas de nutrientes por escorrentía evaluadas en este estudio, podrían comprometer la sostenibilidad de estas plantaciones sometidas a un manejo intensivo en suelos de baja fertilidad. Por tanto, ya que el incendio es la perturbación desencadenante del aumento de nutrientes subsiguiente, son necesarias acciones de selvicultura preventiva en estas plantaciones para la sostenibilidad de estas masas.

Palabras clave: fuego forestal; corta; pérdidas por disolución; entradas precipitación.

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Introduction

In areas of high fire risk the optimal rotation length of plantations and forests could be shortened (Spittlehouse and Stewart, 2003), reducing the financial incomes from harvesting operations and increasing the risk of making unsustainable some type of forest management (McCarthy, 2005).

A good example of this takes place in Galicia (NW Spain), an area that has a 47% of forest fires in Spain over the last 11 years (Ministerio Medio Ambiente, 2006) and where *Eucalyptus globulus* Labill. plantations have undergone a rapid expansion in recent decades, reaching about 175,000 ha in monocultures and 160,000 ha (Ministerio de Medio Ambiente, 2001) in mixed stands in the region. These stands, growing in poor soils, are subjected to an intensive management with short rotations, implying a considerable nutrient export in an area in a short time. Increases in wildfire frequency and burned area are expected under the probable future climate scenarios in NW Spain (Vega *et al.,* 2009) and may significantly affect these eucalypt plantations.

Moreover, the sequence wildfire-clearcutting-thinning is common in eucalypt plantations in the area potentially exacerbating nutrient losses. Although increases in nutrient concentrations or exports have been extensively reported to follow wildfire (*e.g.* Cornish and Binns, 1987; Mackay and Robinson, 1987; Belillas and Rodá, 1993; Ferreira *et al.*, 2005), clearcutting and thinning (*e.g.* Martin *et al.*, 2000; Swank *et al.*, 2001; Wang *et al.*, 2006), the consequences of these three consecutive perturbations on water quality and nutrient export have not been evaluated until now. One important criterion for sustainable land use is that nutrient losses and gains are balanced and that the ecosystem maintains regulation of water and nutrient cycle functions (Wilcke *et al.*, 2009).

Previous studies in NW Spain have investigated the effects of biomass harvesting on nutrient pools in these types of plantations (Dambrine *et al.*, 2000; Merino *et al.*, 2005). Soil erosion losses after harvesting of eucalypt stands (Fernández *et al.*, 2004) have also been evaluated, but the nutrient exports in streamwater after harvesting or thinning have not been evaluated. A complete assessment of nutrient export from forested catchments is crucial as a basis for managing long-term site fertility (Yusop *et al.*, 2006), and for preserving the quality of dependent ecosystems, particularly aquatic ecosystems (Ranger and Turpault, 1999).

The aim of the present study was to determine the changes in dissolved nutrient export in streamflow produced by a perturbation and subsequent forest management activities in a representative *E. globulus* watershed in NW Spain. More specifically, we hypothesize that the above sequence of perturbations in a short period of time would cause a continued increase in nutrient concentrations in streamflow and a pronounced unbalance between nutrient inputs in precipitation and outputs in streamflow. Secondary hypothesis were that wildfire impact would be greater than clearcutting impact and that clearcutting would induce more changes than thinning.

Materials and methods

Study area

The experimental area is located close to the Atlantic Ocean inlet of Pontevedra (42°26’40”-42° 27’ 00” N and 8° 43’ 30”-8° 43’ 55” W). Catchment area is 9.9 ha and it was completely covered by an *E. globulus* plantation. Mean slope is 20%. Main understory species are *Acacia melanoxylon* and *Ulex europaeus*.

The climate in the area is oceanic, temperate and rainy. Mean annual temperature is 14°C. Mean temperature in the coldest month is 9°C and 20.5°C in the hottest month. Average annual precipitation is 1,880 mm y^{-1} and 41% of this falls in the period October-December. There is a dry period in summer (July-September) when 12% of annual precipitation falls.

Soils are Alumiumbric Regosols (FAO, 1998), sandy and sandy-loam textured and developed on granitic parent material. The main soil characteristics are listed in Table 1. More detailed information can be found in Dambrine *et al.* (2000).

Initially this experiment was designed to test the effect of different management practices on water yield and nutrient budgets in two representative *E. globulus* experimental catchments, in a classical paired watershed approach. With this objective, two similar and closely situated *E. globulus* covered catchments were selected in the experimental area in 1987. In 1988, only one year after the start of the study, a wildfire severely affected one of the catchments and in 1989, another wildfire also burnt the Castrove catchment used in the study. Consequently, the free perturbation period comprises the water years 1987-1988 and 1988-1989.

Table 1. Main characteristics of Castrove soils

Depth (cm)	Texture Sand (%)	Texture Silt (%)	pH	C (%)	C/N	Exchangeable vcations [cmol (+) kg^{-1}] Ca	Mg	Na	K	Available P [cmol (+) kg^{-1}]	Exchangeable cation capacity [cmol (+) kg^{-1}]
0-20	73	8	4.5	10.8	17.4	0.01	0.03	0.14	0.07	0.06	3.7
20-50	70	10	4.9	5.4	18.1	< 0.01	0.02	0.04	0.02	0.03	2.7
50-100	72	10	4.8	3.1	19.4	< 0.01	< 0.01	0.03	< 0.01	0.01	1.6

Perturbations and silvicultural treatments during the study

In July 1989, a wildfire affected the watershed. The fire was a moderately intense surface fire which burned understory and scorched most of trees crown. The estimated mean fireline intensity was about 2,700 kW m^{-1} (Van Wagner, 1973).

The forest plantation of the catchment was totally clearcut in summer 1992. Bark was removed with the bole and the logging slash burned. Such a delayed harvesting of eucalypt, three years after fire, is not usual in the area but it provided us with an opportunity to examine the short-term impact of fire on streamflow without the interference of logging (usually carried out in the first year following fire in the area). The next forest operation was sprout selection thinning (reduction of 70% of basal area) was made in 1995-1996, as is common in the area. Thinning slash was left spread on the ground.

Data collection and statistical analysis

Mean precipitation was obtained from a network of carefully located rainfall gauges. Precipitation was also registered continuously. Grab samples of precipitation were collected manually at weekly intervals. Data of annual rainfall during the period of study are listed in Table 2.

Streamflow was continuously measured at the outlet of the catchments using 90° V-notch weirs with standard ink scripture limnigraphs (OTT Kempten). Charts were digitised, and runoff calculated according to the shape of the weir and the corresponding data added at weekly intervals. Automatic samplers were used to sample streamflow proportionally to the water flow and samples were stored and collected at weekly intervals. The water samples were filtered (0,45 µm), then Ca and Mg were analysed by absorption, K and Na by emission, and NO_3^-, and PO_4^{3-} by ion chromatography. Nutrient fluxes were determined by multiplying the measured concentration of dissolved chemicals in the samples by the respective amounts of precipitation or stream water during the period. The nutrient budgets were calculated considering a water year from October to September.

The differences in the mean monthly values of nutrient concentrations between the pre-disturbance period and each of post-wildfire year were evaluated by a Mann-Whitney test. Previously, we verified that the requirements of non-autocorrelation were met.

Table 2. Precipitation and streamflow values during the period of study in the Castrove experimental watershe

Treatment or perturbation	Period of analysis	Precipitation (mm year^{-1})	Streamflow (mm year^{-1})
Wildfire	October 1989-September 1990	1,741	1,155
	October 1990-September 1991	2,497	1,624
	October 1991-September 1992	1,482	550
Clearcutting	October 1992-September 1993	1,750	1,283
	October 1993-September 1994	2,593	1,853
	October 1994-September 1995	2,101	1,301
Thinning	October 1995-September 1996	2,314	1,454
	October 1966-September 1997	1,746	1,148
	October 1997-September 1998	2,305	1,498
	October 1998-September 1999	1,871	936

The same analysis was performed to evaluate the significance of differences in the mean monthly values of nutrient concentration for each of post-clearcutting year and the previous one and for each of post-thinning year and the previous one, respectively.

The SPSS (2004) statistical package was used to carry out the analyses.

Results

Water yields

Streamflow values during the period of study are summarized in Table 2. Water yields relative to the precipitation were higher the first year after clearcutting (73% of precipitation) compared to wildfire (66%) or thinning (63%). This pattern was also observed during the second year after perturbations. Similar values were observed after clearcutting and thinning the third year after these forestry operations.

Changes in nutrient concentrations

Increased concentrations were observed for all the ions (except P) in the first year after wildfire and also for Mg and N during the second year after fire (Fig. 1; Table 3). No significant changes were observed in the third year after wildfire.

Harvesting activities promoted an increase in concentrations of Ca, Mg and K during the first two years after harvesting (Fig. 2; Table 4). Clearcutting caused a increase in N concentrations that lasted three years. Increased concentrations of K during the first year after coppice sprout selection were the only significant change detected in the four years after this forestry operation (Fig. 3; Table 5).

Nutrient budgets

Nutrients budgets calculated to estimate the impact of the measured increases the impact of nutrient

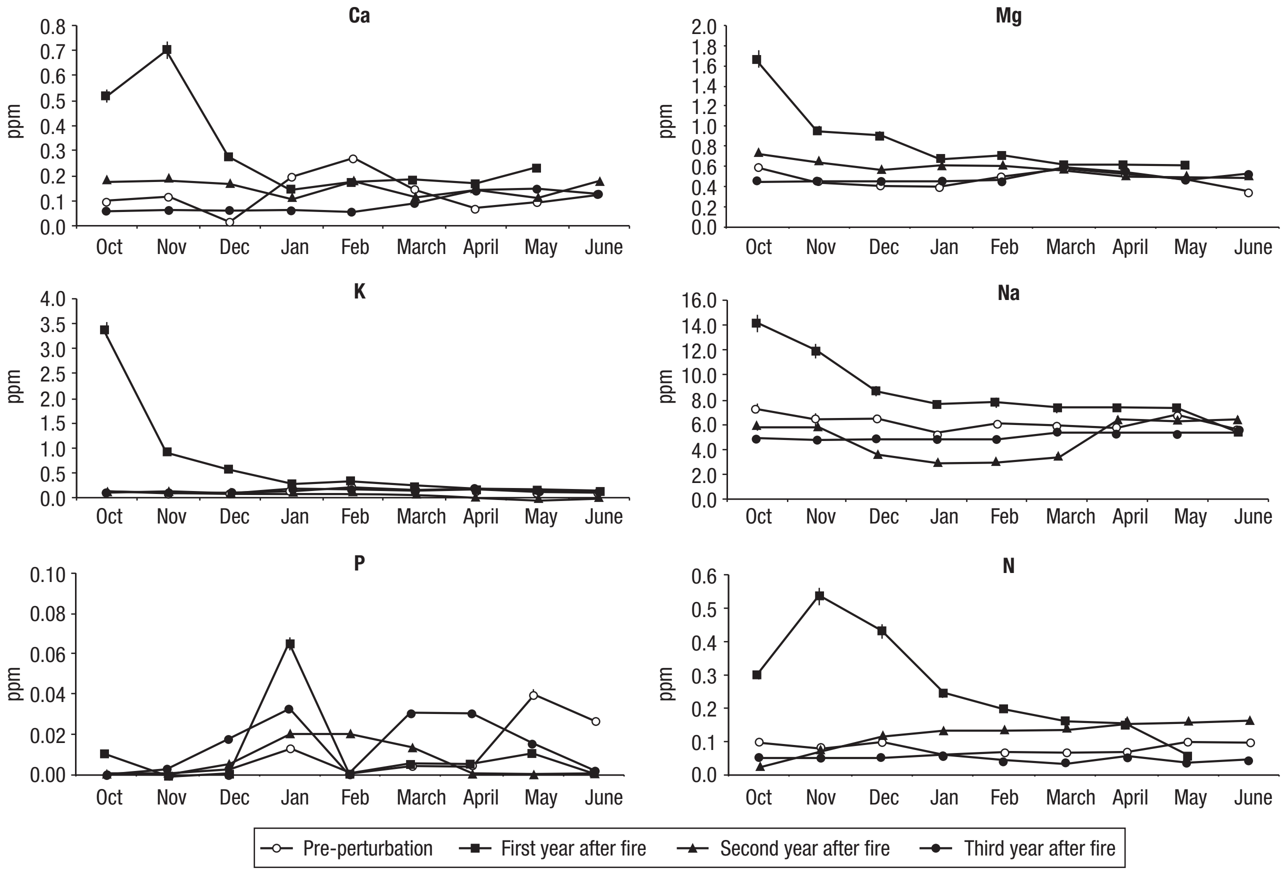

Figure 1. Variation of mean monthly concentrations of cations and anions in streamflow before and after wildfire in the Castrove experimental watershed. Vertical bars, standard error.

Table 3. Mean annual concentrations (mg kg^{-1}) of cations and anions in the period pre-perturbation and after wildfire in the Castrove experimental watershed. In brackets, standard error

	Pre-perturbation	First year after fire	Second year after fire	Third year after fire
Ca	0.13 (0.02)^{a}	0.30 (0.07)^{b}	0.15 (0.02)^{a}	0.10 (0.01)^{a}
Mg	0.47 (0.02)^{a}	0.74 (0.14)^{b}	0.58 (0.03)^{b}	0.49 (0.02)^{a}
K	0.14 (0.01)^{a}	0.65 (0.35)^{b}	0.10 (0.02)^{a}	0.15 (0.01)^{a}
Na	6.2 (0.50)^{a}	7.0 (1.30)^{a}	4.6 (0.60)^{b}	5.0 (0.10)^{b}
P	0.01 (0.03)^{a}	0.01 (0.001)^{a}	0.01 (0.001)^{a}	0.01 (0.001)^{a}
N	0.08 (0.004)^{a}	0.23 (0.06)^{b}	0.12 (0.02)^{b}	0.04 (0.01)^{a}

Means indicated with the same letter within the same row are not significantly different ($P < 0.05$).

exports on system sustainability, revealed that precipitation inputs did not compensate for Mg and N losses in the first and second years after wildfire, or for K in the first year (Table 6). Negative K and N budgets were observed for the first year after harvesting (Table 7). For N, this situation was maintained throughout the post-harvesting period. Nutrient exports after coppice sprout selection thinning mainly compensated for precipitation inputs (Table 8), except for N, in the first year after this forestry operation.

Discussion

The effects of the sequence wildfire-clearcutting-sprout thinning on water yield in this watershed was broadly discussed in a previous published paper (Fernández *et al.*, 2006). Increased water yields were observed during the first three years after wildfire, clearcutting or sprout thinning. These increases were higher after clearcutting followed by wildfire and sprout thinning and significantly correlated with precipitation.

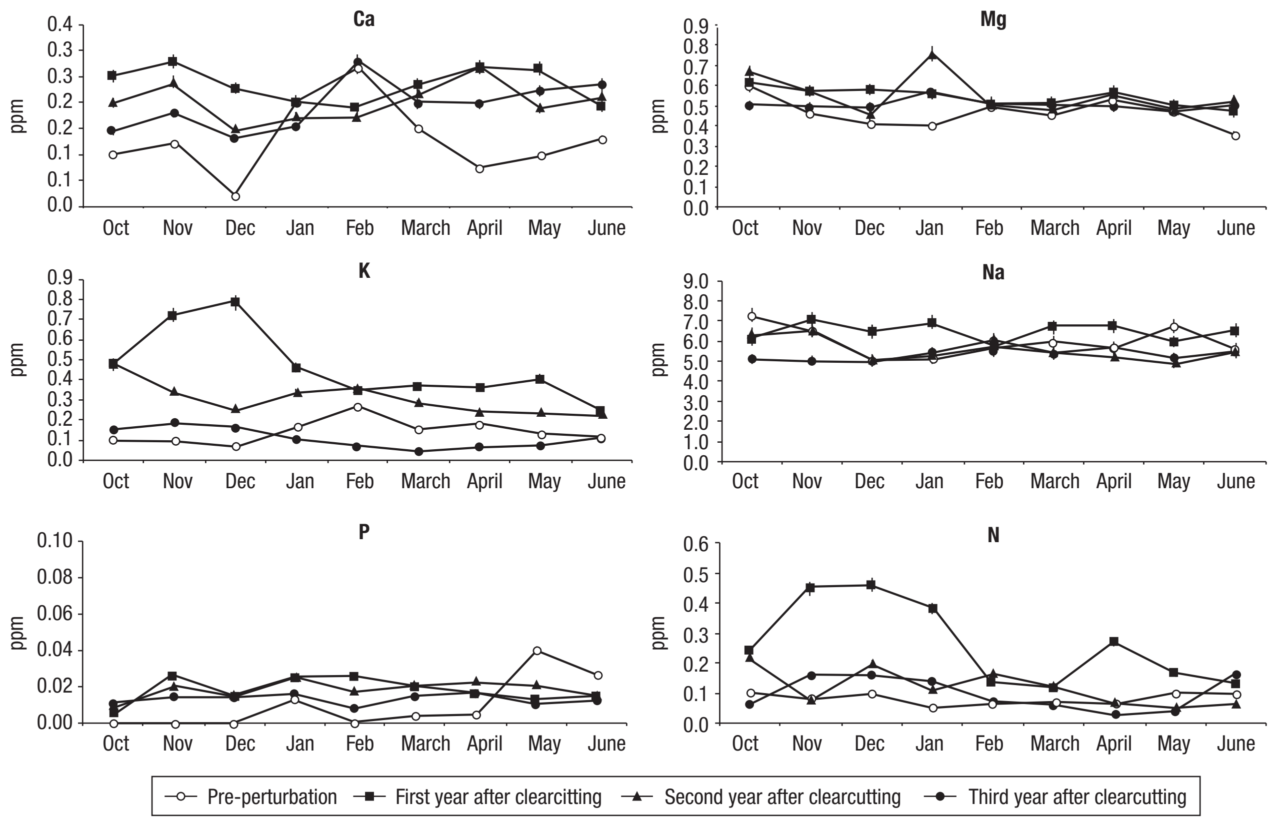

Figure 2. Variation of mean monthly concentrations of cations and anions in streamflow before and after clearcutting in the Castrove experimental watershed. Vertical bars, standard error.

Table 4. Mean annual concentrations (mg kg-$^{-1}$) of cations and anions after clearcutting in the Castrove experimental watershed. In brackets, standard error

	Third year after fire	First year after clearcutting	Second year after clearcutting	Third year after clearcutting
Ca	0.10 (0.01)^{a}	0.20 (0.01)^{b}	0.19 (0.01)^{b}	0.15 (0.02)^{a}
Mg	0.49 (0.02)^{a}	0.55 (0.01)^{b}	0.55 (0.03)^{b}	0.50 (0.01)^{a}
K	0.15 (0.01)^{a}	0.47 (0.06)^{b}	0.30 (0.03)^{b}	0.10 (0.02)^{a}
Na	5.0 (0.10)^{a}	6.5 (0.50)^{b}	5.6 (0.60)^{a}	5.3 (0.10)^{a}
P	0.01 (0.001)^{a}	0.02 (0.01)^{a}	0.02 (0.01)^{a}	0.01 (0.01)^{a}
N	0.04 (0.01)^{a}	0.26 (0.05)^{b}	0.12 (0.02)^{b}	0.10 (0.02)^{b}

Means indicated with the same letter within the same row are not significantly different ($P < 0.05$).

Few studies have evaluated the evolution of dissolved nutrient losses after such perturbations like those in this study although, as in the present study, previous research has reported significant increases in ion concentrations and loads, especially K and nitrate, after wildfire (*e.g.* Cornish and Binns, 1987; Malmer, 2004; Ferreira *et al.*, 2005). However, comparison among results is difficult because the magnitude of the effects of fire on water quality is dependent on how fire characteristics (fire behaviour, fire severity or fire timing) interact with watershed characteristics (Ranalli, 2004; Elliott and Vose, 2005). The increased nutrient loss following fire has been attributed to increased nutrient leaching from the surface layer of ash, resulting from the combustion of litter layer and ground vegetation, that contains a high concentration of nutrients (Belillas and Rodá, 1993; Ferreira *et al.*, 2005). In fact, the increase observed in K concentration in this study is consistent with the high concentration of K measured in *E. globulus* ash by Soto and Díaz-Fierros (1993). The high

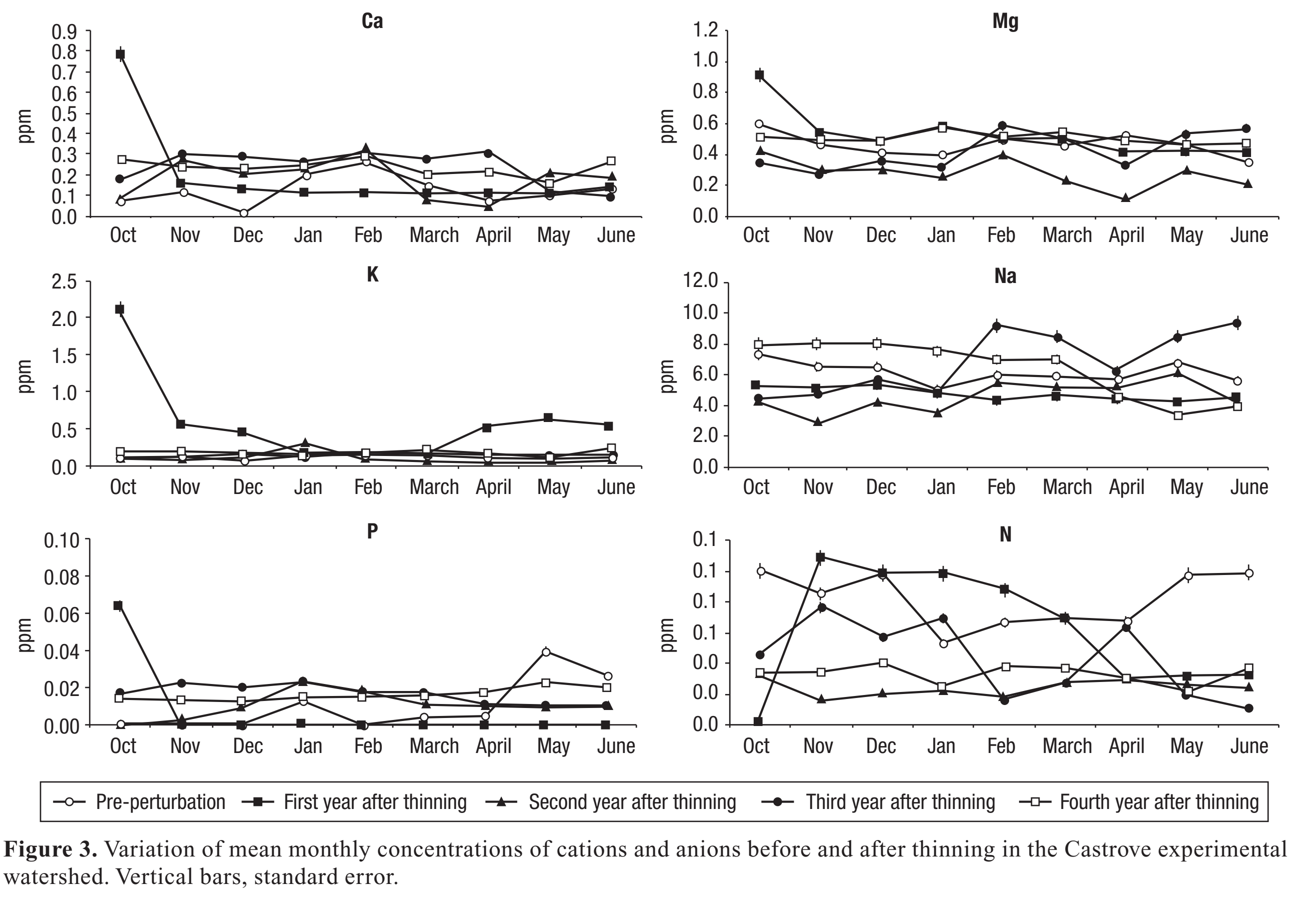

Figure 3. Variation of mean monthly concentrations of cations and anions before and after thinning in the Castrove experimental watershed. Vertical bars, standard error.

Table 5. Mean annual concentrations (mg kg^{-1}) of cations and anions after thinning in the Castrove experimental watershed. In brackets, standard error

	Third year after clearcutting	First year after thinning	Second year after thinning	Third year after thinning	Fourth year after thinning
Ca	0.15 (0.02)[a]	0.20 (0.07)[a]	0.21 (0.03)[a]	0.20 (0.03)[a]	0.20 (0.03)[a]
Mg	0.50 (0.01)[a]	0.50 (0.05)[a]	0.40 (0.03)[a]	0.40 (0.04)[a]	0.40 (0.01)[a]
K	0.10 (0.02)[a]	0.60 (0.20)[b]	0.10 (0.03)[a]	0.14 (0.02)[a]	0.17 (0.02)[a]
Na	5.3 (0.10)[a]	4.7 (0.15)[b]	4.6 (0.30)[a]	6.0 (0.70)[a]	6.0 (0.70)[a]
P	0.01 (0.01)[a]	0.01 (0.01)[a]	0.01 (0.01)[a]	0.02 (0.01)[a]	0.02 (0.01)[a]
N	0.10 (0.02)[a]	0.06 (0.01)[a]	0.04 (0.01)[a]	0.04 (0.01)[a]	0.03 (0.01)[a]

Means indicated with the same letter within the same row are not significantly different ($P < 0.05$).

N concentrations after fire has been frequently associated to increased nitrification in soil and remaining forest floor (De Bano *et al.*, 1998; De Luca *et al.*, 2006), being the nitrate easily leached into the ground water.

The little modifications in P concentrations observed in this study, contrast with the elevated stream concentrations during several years observed after wildfire by Ambrosia *et al.* (1997) and Hauer and Spencer (1998). In our case, the acidity of the soils could have favoured P retention.

Much information has been collected in temperate regions as regards nutrient losses resulting from harvesting or thinning (Martin *et al.*, 1984; Hornbeck *et al.*, 1986; Harr and Fredriksen, 1988; Tiedemann *et al.*, 1988; Martin *et al.*, 2000; Swank *et al.*, 2001; Wang *et al.,* 2006; Stednick, 2008) or from clearcut and fire (Feller and Kimmins, 1984; Cornish and Binns, 1987). Generally, the impact on nutrient concentrations and exports varies with the degree of disturbance, but site-specific factors associated with soil and vegetation characteristics are also important. From this point of

Table 6. Atmospheric input and hydrologic loss of nutrients after wildfire (kg ha^{-1}) in the Castrove experimental watershed

Water year		Ca	Mg	K	Na	P	N
89-90	Precipitation Input (I)	5.0	6.4	6.1	90.0	0.22	1.2
	Observed Stream water output (O)	3.8	9.3	5.8	102.6	0.01	3.9
	I-O	1.2	–2.9	–0.3	–12.6	0.21	–2.7
90-91	Precipitation Input	6.3	6.7	5.1	55.0	0.23	1.0
	Observed Stream water output	2.2	9.8	1.5	53.3	0.20	1.8
	I-O	4.1	–3.1	3.6	1.7	0.03	–0.08
91-92	Precipitation Input	4.0	4.0	4.0	28.0	0.42	0.5
	Observed Stream water output	0.5	2.6	1.6	27.4	0.07	0.2
	I-O	3.5	1.4	2.4	0.6	0.35	0.3

Table 7. Atmospheric input and hydrologic loss of nutrients after clearcutting (kg ha^{-1}) in the Castrove experimental watershed

Water year		Ca	Mg	K	Na	P	N
92-93	Precipitation Input (I)	4.7	7.4	4.4	88.1	0.30	0.6
	Observed Stream water output (O)	3.1	7.2	8.1	86.7	0.30	4.6
	I-O	1.6	0.2	–3.7	1.4	0.0	–4.0
93-94	Precipitation Input	8.3	10.4	7.3	96.2	0.42	1.5
	Observed Stream water output	3.4	10.3	5.6	94.7	0.40	2.7
	I-O	4.9	0.1	1.7	1.5	0.02	–1.2
94-95	Precipitation Input	4.9	6.8	4.4	56.0	0.40	0.8
	Observed Stream water output	2.6	6.5	1.3	55.5	0.15	1.3
	I-O	2.3	0.3	3.1	0.5	0.25	–0.5

Table 8. Atmospheric input and hydrologic loss of nutrients after sprout thinning (kg h^{-1}) in the Castrove experimental watershed

Water year		Ca	Mg	K	Na	P	N
95-96	Precipitation Input (I)	5.4	8.1	5.0	68.3	0.40	0.9
	Observed Stream water output (O)	1.7	7.3	2.4	67.4	0.10	1.2
	I-O	3.7	0.8	2.6	0.9	0.30	–0.30
96-97	Precipitation Input (I)	6.5	7.0	5.0	62.1	0.40	0.8
	Observed Stream water output (O)	3.3	4.5	1.6	61.5	0.13	0.2
	I-O	3.2	2.5	3.4	0.6	0.27	0.6
97-98	Precipitation Input (I)	5.4	7.1	5.7	78.4	0.30	1.0
	Observed Stream water output (O)	4.4	4.8	1.8	77.6	0.20	1.0
	I-O	1.0	2.3	3.9	0.8	0.10	0.0
98-99	Precipitation Input (I)	5.1	6.0	4.2	63.0	0.32	0.6
	Observed Stream water output (O)	1.7	4.7	1.0	62.6	0.21	0.3
	I-O	3.4	1.3	3.2	0.4	0.11	0.3

view, there is no available information on the impact of the sequence harvesting-coppice sprout thinning after wildfire in these eucalypt stands growing in unsaturated soils. Mackay and Robinson (1987) investigated the effects of logging and wildfire on eucalypt catchments in Australia. They reported losses of 3, 4 and 5 kg ha^{-1} for K, Ca and Mg, respectively, slightly lower values than those obtained in the present study. The moderate changes observed in P concentrations after harvesting or thinning agrees with the findings of Swank *et al.* (2001).

Clearcutting temporarily prevents nutrient uptake by vegetation, while decomposition proceeds and increases the amount of available nutrients in the dissolved fraction of soil solution (Hornbeck *et al.*, 1986; Yusop *et al.,* 2006). Greater amounts of soil water resulting from reduced interception and transpiration provide a means of transport to streams (Brooks *et al.*, 2003). The increase in nutrient concentrations and load may also have been related to soil disturbance and sediment movement (Wang *et al.*, 2006), although soil erosion losses measured after harvesting in an adjacent similar eucalypt stand were only moderate or low (Fernández *et al.*, 2004).

Increased available mineral N was attributed to increases in soil N mineralization as observed after clearcutting and slash burning in a nearby eucalypt stand (Fernández *et al.*, 2009).

The magnitude of nutrient export in our case was influenced by both increased discharge resulting from reduced evapotranspiration (Fernández *et al.*, 2006) and increases in solute concentrations. Na budgets were equilibrated in most cases, confirming, thus the hydrologic budget (Dambrine *et al.*, 2000). In the first water year after fire (89-90), the slightly higher Na outputs in relation to precipitation inputs, could be related with the suppression activities (aircrafts spreading ocean water).

Elevated nutrient concentrations and imbalances were not continued during the period of study, rejecting, thus, our first hypothesis. As we hypothesized, the higher impact in nutrient concentrations and budgets was caused by wildfire followed by harvesting and sprout thinning.

Nutrient extraction in biomass harvesting measured in an adjacent site at the end of the rotation period (15 years) were quantified in 120 kg ha^{-1} of Ca, 96 kg ha^{-1} of P, 89 kg ha^{-1} of K and 56 kg ha^{-1} of Mg (Dambrine *et al.*, 2000). Nutrient losses in streamflow during the period of study (Tables 6, 7 and 8) count for 23% of Ca, 120% of Mg, 2% of P and 36% of K of the amount removed in biomass, respectively. These values are nor negligible, although atmospheric deposition exceeds the elevated losses in most years. Moreover, atmospheric inputs are underestimated in our case, as dry deposition was not measured. The amount of nitrate lost in streamwater seems to be compensated in excess by in situ nitrification in this site (Fernández *et al.*, 2009).

Conclusions

This study provided information on the nutrient export response to wildfire and intense forest management in a representative *E. globulus* catchment in

Galicia. Although the studied sequence is common in the area, the consequences on watershed nutrient balances had not been evaluated until now.

Wildfire caused the highest change in nutrient concentrations and loads. The effect of wildfire on nutrient export appeared to last two years although the nutrient outputs in streamwater were generally compensated by precipitation inputs, except for Mg and nitrate. The response to clearcutting was more pronounced in the following two years, particularly for K and nitrate. The changes induced by sprout thinning in *E. globulus* indicated that the nutrient exports were mainly balanced by nutrient inputs via precipitation, except for nitrate the first year after thinning.

However, the low fertility of the soils and the relatively low potential of cation replenishment of soils where this fast-growing species lives show the fragility of these type of ecosystems. Wildfire by itself seems to be the main perturbation affecting nutrient imbalances and shortening the rotation period of these plantations. Improvement of preventive selviculture techniques to reduce fire risk, soil rehabilitation after fire, reduction of harvested area, fertilization after clearcutting could be necessary alternatives of forest management in these forest plantations.

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