Ann. For. Sci. 64 (2007) 183–200
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DOI: 10.1051/forest:2006103

Original article

Effects of the clear-cutting of a Douglas-fir plantation (*Pseudotsuga menziesii* F.) on the chemical composition of soil solutions and on the leaching of DOC and ions in drainage waters

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(Received 10 February 2006; accepted 27 September 2006)

Abstract – The effects of the clear-cutting of a 70-year-old Douglas-fir plantation on the chemical composition of soil solutions and on leaching of nutrients in drainage waters were observed by a continuous monitoring, six years before and three years after the cutting. Forest harvesting was made with very limited soil disturbances. Results showed that the concentration of weakly fixed solutions did not change but that the concentration of gravitational solutions of the upper soil layers drastically fell down after the cutting. The limited increase in nutrients leached with drainage waters was only due to the increase in the water flux, which is difficult to quantify because of the presence of ground vegetation. The monitoring of numerous fluxes before and after the clear-cutting could explain the specific behaviour of the soil solutions. The limited losses of nutrients the after clear-cutting in a potentially responsive ecosystem were unexpected. The initial hypothesis was that the decrease in the mineralization and nitrification rates observed after the cutting was related to a stimulating effect of Douglas-fir on the activity of soil nitrifyers.

Douglas-fir / clear-cutting / soil solutions / nutrients / leaching

Résumé – Effet de la coupe à blanc d'un peuplement de Douglas (*Pseudotsuga menziesii* F.) sur la composition chimique des solutions du sol et sur le flux d'éléments drainés. Les effets de la coupe à blanc d'une plantation de Douglas de 70 ans ont été observés sur la composition chimique des solutions du sol et les pertes d'éléments par drainage, par un suivi mensuel pendant 6 ans avant, et 3 ans après la coupe. L'exploitation du peuplement a été réalisée avec une perturbation minimum du sol. Les résultats montrent que les solutions liées ont peu évolué après la coupe, alors que le changement des solutions libres a été drastique dans les horizons de surface du sol. Malgré des incertitudes sur le rôle de la végétation spontanée, le drainage d'éléments n'a pas fortement augmenté après la coupe. La prise en compte de l'ensemble des flux mesurés dans cette étude semble pouvoir expliquer les observations. Les pertes limitées après la coupe d'une plantation où l'activité nitrifiante était élevée avant la coupe étaient inattendues. L'hypothèse avancée est l'arrêt du contrôle stimulateur des populations nitrifiantes du sol après la coupe du Douglas.

Douglas / coupe-à-blanc / solutions du sol / éléments nutritifs / lixiviation

1. INTRODUCTION

Forest management could potentially strongly disturb the ecosystems and caused large injuries to the soil, which is not a completely renewable resource. An intense harvesting, a change in species, a shortening of rotations and a mechanisation of the thinning, harvesting and regeneration operations result in constraints to the physical, chemical and biological properties of the soil [21]. On the other hand, remediation is technically difficult, never definitive and expensive [46].

Clear-cutting is thought to be a specific phase during which large pools of soil nutrients could be lost, due to several causes: (i) the exportation of nutrients associated with the harvested material and as a consequence of slash management (e.g. burning and windrowing), (ii) the scalping and/or removal of forest floor caused by machinery (harvesting and site preparation), (iii) the acceleration of the mineralization of organic matter associated with changes in soil climate, (iv) the chemical erosion due to losses in drainage waters, and (v) the physical erosion when the soil lays bare in a sloping relief [23].

The issue of the loss of nutrients in drainage water is central for soil quality changes and for the impact of forestry in the environment. Situations with noticeable losses [2, 4, 6, 7, 12, 13, 20, 27, 28, 44, 54] or more limited losses of nutrients [16, 43, 57, 58] have been reported. The case of the large losses observed the after clear-cutting of the Hubbard Brook experimental forest represents a very specific situation whose results cannot be directly generalized. The repeated application of herbicides for several years after the harvest, which left the soil without vegetation explains that specific case rather well [38].

The rate of soil organic matter mineralization and more specifically the rate of nitrate production were recognized as driving processes explaining the nutrient losses by drainage after the clear-felling [17]. Vitousek et al. [64] described the relevant parameters associated with nitrate losses as a response to ecosystem disturbance. Nevertheless, even with a rather abundant amount of literature, it is always difficult to predict what

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Table I. Main characteristics of the soil of the site before the harvest.

Hor.	Depth (cm)	$pH(_{H20})$	Clay	Silt	Sand	OM	N	C:N	Ca	Mg	K	Na	Al	CEC	BS (%)
			(%)			(%)			$cmol_c\ kg^{-1}$						
A_1	0–17	4.3	24	39	37	6.3	0.30	12.3	0.3	0.10	0.23	0.03	5.7	14.6	4.5
A_2	17–37	4.4	26	45	29	3.4	0.17	11.8	0.1	0.03	0.11	0.03	4.4	10.2	2.6
(B)	37–60	4.4	27	33	36	1.0	0.06	9.6	0.1	0.02	0.11	0.02	3.9	6.9	3.5
(B)/C	60–90	4.5	14	39	47	0.2	0.02	7.3	0.1	0.02	0.10	0.02	4.0	6.0	4.1

will occur on a specific site. Several factors can explain a difficulty in generalizing the interpretation of observations, among them are the methodology used, the scales investigated (from lysimeter studies at the plot scale to stream-water at the catchment scale), and the specific site conditions (soil and vegetation types). Due to specific changes in solution chemistry occurring in the subsoil, the plot scale is generally the most relevant one for observing soil quality changes, while the catchment scale is appropriate for studying the constraints to the environment [35, 47].

The objective of this study was to investigate the changes in soil solution chemistry after the clear-cutting of a mature Douglas-fir stand, using both gravitational and capillary solutions. The chemical composition of soil solutions represent an efficient tool to assess the soil nutrient dynamics because they reacted rapidly to changes, especially if the free and fixed phases were investigated [48, 65]. The hypothesis tested was that the clear-cutting would increase the concentration of soil solutions and the drainage losses in a site where the mineralization and nitrification rates where high before the cutting.

This study is part of a larger project which aims to study the impact of Douglas-fir cultivation on soil nutrient budgets calculated for the whole rotation period, including the regeneration period. The objectives concerned both basic and applied research.

2. MATERIALS AND METHODS

2.1. Site and stand characteristics

The study site is located in the Beaujolais Mounts in France (46° 30' N, 4° 38' E) at an elevation of 750 m. The mean annual temperature is 8.5 °C and the mean annual rainfall was 1020 mm for the period 1950–1980 [36]. A chrono-sequence of three mono-specific plantations, aged 20, 40 and 60 in 1992, was selected to represent the dynamics of development of the older stand. One plot of 0.5 ha per stand was continuously monitored from 1992 to 2001 for biogeochemical nutrient cycling studies and nutrient budget calculations [49]. The 66-year-old stand was clear-cut in November 1998, and re-planted with Douglas-fir in March 1999 in order to calculate the nutrient budgets for the whole rotation, including the harvest and regeneration period.

Before the clear-cutting in the autumn of 1998, the 66-year-old stand had the following characteristics: 206 trees per ha; 40 m as average height; 166 cm as mean circumference at breast height (CBH). *Rubus fruticosus* L., *Senecio nemorensis* F., *Rubus idaeus* and *Digitalis purpurea* L. dominated the ground vegetation raising a biomass of 2.8 t ha^{-1} before the clear-cutting and of 4.8, 4.3 and 4.3 t ha^{-1} in 1999, 2000 and 2001 respectively.

The soil was an Alocrisol [3] developed from the weathering of a volcanic tuff from the Visean (Carboniferous) period. Soil texture was sandy loam. Humus was of the moder type. The carbon content of the upper soil layer was rather high (8% in the A_{11} horizon). The soil was acidic with a pH ranging from 4.3 to 4.5, depending on horizons. Base saturation was low (lower than 10 in all horizons including the A_1) (Tab. I) [40].

The stand was felled with keeping all the measurement systems active (lysimeters, soil moisture probes (TDR) and temperature probes). In the present situation, the clear-cutting was made with very little disturbance to the soil. Slashes were manually windrowed outside the measurement area. The vegetation was only manually controlled once a year, one square meter around the young trees (about 1000 seedlings per ha).

The main methodologies used in this study have already been described in several reports, especially when presenting the nutrient budgets calculated after three and six years of monitoring [41, 49].

2.2. Flux measurements

2.2.1. Atmospheric deposition

Total atmospheric deposition was assumed to be the sum of wet deposition (WD), dry deposition (DD) and direct uptake of nutrients in the canopy (Cup). WD was measured from bulk precipitation and DD was calculated from throughfall solutions because of the lack of reliable measurement methods for DD and Cup fluxes. The calculation described by Ulrich and Pankrath [59] was used, assuming in the present situation that Na^+ was a tracer for P, K^+, Ca^{2+} and Mg^{2+}, and SO_4^{2-} was a tracer for NH_4^+ and NO_3^-. Such a calculation led to minimum values for direct adsorption by the canopy, especially for N, the most concerned element. Rainfall was collected outside the stand by a daily collector system; throughfall was collected by three double gutters (2.17 × 0.12 m) placed in such a way as to integrate the discontinuity of the forest canopy. Stemflow was collected by plastic collars fixed around the trunks of 10 trees selected to represent the different growth classes.

2.2.2. Soil solutions

Two types of solutions were collected: (i) gravitational solutions using zero-tension plate lysimeters (ZTL) made up of polyethylene because they are the solutions really drained out of the soil, and, (ii) capillary solutions collected by tension-cup ceramic lysimeters, because they are closer to the nutritive solution of the vegetation [48].

ZTL solutions were collected at the basis of the forest floor by a set of 27 thin tensionless lysimeters (40 × 2.5 cm) gathered in groups of nine (3 replicates) in order to represent approximately the same area as a ZT plate lysimeter inserted in the mineral soil. They were designed to disturb the continuity between forest floor and mineral soil as little as possible. Four replicates of lysimeters (40 × 30 cm) connected to one common container per soil layer were introduced into the soil profile from a pit which was backfilled after the installation, at a depth of 15, 30, 60 and 120 cm. Solutions were collected downhill in pits where they were protected from light and extreme variations in temperature. Samples were collected monthly for a period running from July 1992 to October 2001.

TL-solutions were collected from ceramic cup lysimeters connected to a vacuum pump which maintained a constant suction of –600 hPa. Eight replicates were set up at 15, 30, 60 and 120 cm. Cup-lysimeters were installed horizontally from the side of a pit with a mean distance of 1.5 m between replicates. TL-solutions were collected monthly from July 1997 to October 2001.

2.3. Analytical methods

After being collected in the field, the solutions were brought back to the laboratory for a rapid treatment. They were immediately filtered (0.45 μm), maintained at 4 ˚C, and analysed as quickly as possible (in general, in the week following the collection). Each replicate of TL solutions was analysed separately whereas, because of the experimental design, ZTL solutions were pooled for analysis. The pH was measured after filtration with a single-rod pH electrode (INGOLD-XEROLIT®) connected to a Mettler DL21 pH-meter. Nitrate, ammonium and chloride were measured by colorimetry (first on aTechnicon auto-analyzer II from 92 to 96, then on a microflux Traacs analyser; intercalibration tests were made when changing the method), NO_3^-, Cl^- and SO_4^{2-} were also analysed by ionic chromatography on a DIONEX DX 300, from winter 1994. Total Si, S, P, K, Ca, Mg, Mn, Na, Fe and Al concentrations were measured by ICP emission spectroscopy (JY 38+ spectrometer since 92 to 98 and then on JY 180 Ultrase). Total organic carbon (DOC) was measured on a SHIMADZU TOC 5050. Al speciation was periodically made according to Boudot et al. [10].

2.4. Data base and procedure for treatment of data

All field and laboratory measurements and the model-generated data used for budget calculations were administrated by an Access database (Microsoft) using VBA programming. Statistical procedures used Excel (Microsoft) and Unistat software applications. Data processing was carried out in several stages, using ANOVA test on every single measurement, before and after the clear-cutting (test of Student-Newman-Keuls), and descriptive statistical studies (mean values, standard deviations) for studying variability of data between replicates of collectors when possible, between collector types and between seasons and years (time variation). No time series were considered for the data treatment because three years after the cutting represent too short a period.

2.5. Water budget

ZT plate lysimeters are suitable for unbiased soil solution chemistry, but they only collect part of the soil solutions. A water budget is therefore necessary to quantify the nutrient fluxes. Water budget was derived from the Granier et al. model [25] and adapted for the site by Villette [62]. A detailed description of the model was given by Marques et al. [41]. This compartment and flux model operated with the following parameters: incident precipitation (measured); throughfall (measured); tree transpiration (estimated from Potential Evapo-Transpiration provided by the meteorological station of Tarare situated 50 km south of the site) and regulated by the extractable soil water content and by the wetness of the foliage [25]; direct soil evaporation (estimated from the global radiation decrease between open area and under tree cover); soil water holding capacity (measured). In order to estimate the impact of the clear-cutting on the nutrients lost by drainage, the initial water budget was modified to eliminate the tree uptake and take into account the ground vegetation. As no measurements were made on the ground vegetation, scenarios were tested to evaluate the sensitivity of the drainage to the ground vegetation behaviour.

The tested scenarios were based on the following observations or hypotheses made according to the literature: (i) tree interception and transpiration disappeared, (ii) interception of rainfall by ground vegetation was assumed to vary from 5 to 10% of the incident precipitation (it was about 20% with trees), (iii) ground vegetation transpiration was assumed to vary from 35 to 40% of PET (it was 65% for trees), (iv) direct soil evaporation was expected to vary from 20 to 25% of PET (it was 5% with the stand), and (v) root distribution of ground vegetation was assumed to be more superficial (60% between 0 and 15 cm, 30% between 15 and 30 cm, 10% between 30 and 60 cm and no roots below 60 cm) compared to the root distribution observed for trees (34% between 0 and 15 cm, 29% between 15 and 30 cm, 30% between 30 and 60 cm and 7% between 60 and 120 cm). Scenario 1 corresponds to the lowest values of all parameters e.g. 5% for interception, 35% for transpiration and 20% for direct evaporation and scenario 2 corresponds to the highest values.

Fluxes of elements were obtained by multiplying the appropriate weighted concentrations with the water fluxes calculated by the model.

In June 1997, a TDR-system (Trase from Soil Moisture^{LT}) was installed in the stand to compare the soil moisture measurements with the theoretical values calculated by the model. Probes were left into the soil to quantify the effect of the clear-cutting on soil moisture. Due to some problems with the absolute calibration of the material – that were only understood and solved when two different apparatuses had been used for the same measurements –, only relative changes in soil moisture after the clear-felling can be used. Unfortunately, it was impossible to compare the soil moisture measurements with the model outputs.

3. RESULTS

3.1. Spatial and temporal variability

3.1.1. Replicated collectors in the field out-coming to a unique container and/or, samples were pooled for the chemical analysis

This was the case for rainfall (3 collectors), stemflow (10 collectors), and gravitational solutions (4 ZTL collectors at 15, 30, 60 and 120 cm). Only the temporal variability of concentration can be studied.

For example, for ZTL, spatial variability was supposed to be integrated, because the number of collectors was defined from previous studies where spatial variability had been

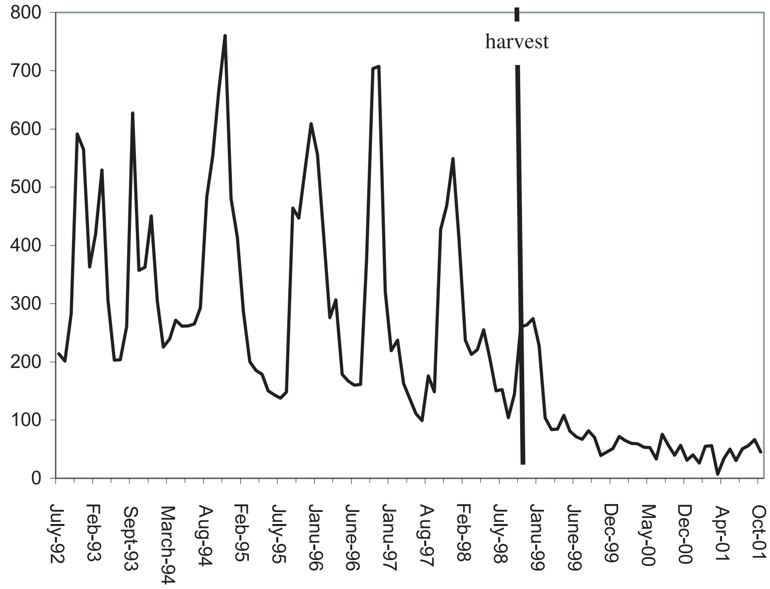

Figure 1. Evolution of Ca^{2+} concentration (in $\mu mol_c\ L^{-1}$) in gravitational solutions at 15 cm depth, before and after clear-cutting (vertical line).

tested [18]. The temporal variability was related to seasons with maximum values occurring in autumn. The clear-cutting effect was very clear on time variation : gravitational solutions showed a strong reduction in their concentration for a majority of elements. The example of Ca^{2+} in ZTL solutions at 15 cm illustrated the time variability, with rather stable mean annual concentrations and clear seasonal cycles before the cutting and very low values and no seasonal trends after the clear-cutting (Fig. 1).

3.1.2. Replicated collectors where solutions were individually collected and analysed

This was the case for throughfall (3 groups of 2 collectors), gravitational solutions under forest-floor (3 groups of 9 collectors) and capillary solutions at 15, 30, 60 and 120 cm (8 collectors).

For gravitational solutions under the forest-floor, the concentration of Mg^{2+} illustrated the good general synchronism observed between collectors: spatial variability only resulted in the intensity of identical processes. The hierarchy between collectors was more or less constant before the clear-cutting, but was modified after it. It indicates an interaction between spatial and temporal variability. The temporal variability mainly consisted in seasonal cycles and in the effect of clear-cutting (decrease in concentrations and disappearance of seasonal cycles). The example of Mg^{2+} is presented in Figure 2.

Capillary solutions showed a rather high spatial variability, but a good synchronism generally appeared between the samplers. A hierarchy between the samplers was also observed, and appeared to be partly modified after the clear-cutting, indicating again that the treatment induced some interaction between spatial and temporal variability. The example of NO_3^--N is presented in Figure 3.

The conclusion was that it is appropriate to work on mean values for solution concentrations.

3.2. Concentration of solutions

3.2.1. Rainfall

The mean value for the sum of concentration of cations was 142 $\mu mol_c\ L^{-1}$ (Tab. II). The ionic balance, before and after the clear-cutting, was dominated by an excess of cations, varying from 56 $\mu mol_c\ L^{-1}$ before the clear-cutting to 25 $\mu mol_c\ L^{-1}$ after it. The anion deficit could be explained by the presence of organic anions. The mean DOC concentration of 4.5 mg L^{-1} required a charge of 9 μmol_c per mg of C, which is in agreement with the literature indicating values ranging from 5 to 10 μmol_c per mg of C [61]. Anions in rainfall were dominated by SO_4^{2-} (62 $\mu mol_c\ L^{-1}$ before the clear-cutting and 44 $\mu mol_c\ L^{-1}$ after it) and by NO_3^--N (52 $\mu mol_c\ L^{-1}$ before the clear-cutting and 44 $\mu mol_c\ L^{-1}$ after it). Cations were dominated by NH_4^+ (67 $\mu mol_c\ L^{-1}$ before the clear-cutting and 58 $\mu mol_c\ L^{-1}$ after it) and Ca^{2+} (28 $\mu mol_c\ L^{-1}$ before the clear-cutting and 33 $\mu mol_c\ L^{-1}$ after it). Rainfall pH varied from 5.45 before to 5.85 after the clear-cutting.

The statistical analysis of data obtained before and after the clear-cutting showed very little significant differences between those two periods (significant differences occurred for pH, Cl^- and $H_2PO_4^-$).

3.2.2. Throughfall solutions

The mean value for the total sum of concentration of cations was 392 $\mu mol_c\ L^{-1}$ (Tab. II). The ionic balance was dominated by cations with an excess of 130 $\mu mol_c\ L^{-1}$ over anions.

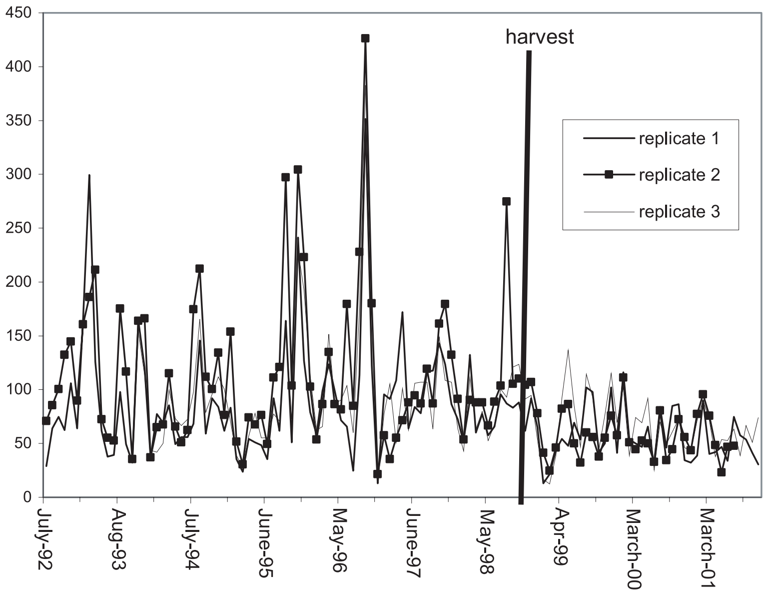

Figure 2. Evolution of Mg^{2+} concentration (in $\mu mol_c L^{-1}$) for gravitational solutions collected under the forest-floor, before and after clear-cutting (vertical line).

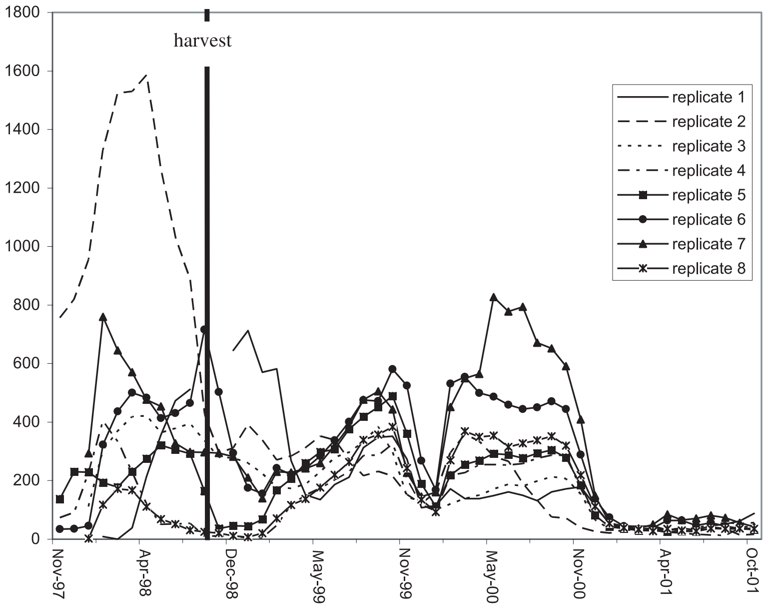

Figure 3. Evolution of NO3$^-$ (in $\mu mol_c L^{-1}$) in capillary solutions collected at 60 cm depth, before and after clear-cutting before and after clear-cutting (vertical line).

The deficit of the ionic balance in anions was attributed to the presence of organic carbon (20 mg L^{-1}) requiring a mean charge of 6.5 μmol_c per mg of C. Anions in throughfall were dominated by NO_3^- (166 μmol_c L^{-1}) and SO_4^{2-} (121 μmol_c L^{-1}). For cations, NH_4^+ dominated (121 μmol_c L^{-1}) and Ca^{2+} (89 μmol_c L^{-1}) came secondarily. The mean throughfall pH was 4.93.

3.2.3. Stemflow solutions

The mean value for total cations was 1148 μmol_c L^{-1} (Tab. II). The ionic balance was dominated by cations with an excess of 318 μmol_c L^{-1}over anions. Again, the deficit of the ionic balance can be explained by organic anions (DOC of 69 mg L^{-1}), requiring a mean charge of 4.5 μmol_c per mg of C. SO_4^{2-} (447 μmol_c L^{-1}) and NO_3^- (302 μmol_c L^{-1}) were the dominant anions. For cations, Ca^{2+} (275 μmol_c L^{-1}) and NH_4^+ (162 μmol_c L^{-1}) dominated. The stemflow pH was very acidic with a mean value of 3.75.

3.2.4. Soil solutions

3.2.4.1. Gravitational solutions

Before the clear-cutting, the total cationic charge varied from 500 to 1000 $\mu mol_c.L^{-1}$depending on the soil layer (Tab. III). The ionic balance presented an anion deficit decreasing from 386 μmol_c L^{-1} under forest-floor to

Table II. Rainfall before and after clear-cutting, throughfall and stemflow before clear-cutting (data in $\mu mol_c L^{-1}$ except pH expressed in pH Units and DOC in mg L^{-1}).

		pH			$H_2PO_4^-$			SO_4^{2-}			H_4SIO_4			Mn^{2+}			Mg^{2+}		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	Test
Rainfall	**Before clear-cutting**	5.5 (0.7)	A	b	0.9 (2.3)	A	a	62.1 (50.6)	A	a	3.6 (3.3)	A	a	0.5 (0.7)	A	a	9.4 (10.3)	A	A
	After clear-cutting	5.9 (0.5)	B	/	1.2 (2.7)	A	/	43.8 (31.0)	A	/	5.0 (5.5)	A	/	0.4 (0.6)	A	/	10.4 (6.8)	A	/
Throughfall	**Before clear-cutting**	4.9 (0.6)		**b**	0.7 (2.1)		**a**	121.0 (88.7)		**a**	2.4 (2.0)		**a**	10.2 (9.4)		**b**	32.5 (23.1)		**B**
Stemflow	**Before clear-cutting**	3.8 (0.5)		**a**	0.2 (1.1)		**a**	447.1 (342.9)		**b**	14.3 (13.9)		**b**	34.9 (28.2)		**c**	83.7 (67.7)		**C**

		Ca^{2+}			Al^{3+}			Na^+			K^+			NO_3^-			NH_4^+		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	Test
Rainfall	**Before clear-cutting**	27.9 (24.1)	A	a	1.5 (2.3)	A	a	25.7 (38.5)	A	a	8.7 (12.5)	A	a	53.3 (49.0)	A	a	66.5 (57.5)	A	A
	After clear-cutting	33.1 (35.5)	A	/	2.2 (3.8)	A	/	31.4 (23.1)	A	/	5.8 (6.4)	A	/	43.6 (39.0)	A	/	58.1 (62.1)	A	/
Throughfall	**Before clear-cutting**	88.4 (64.6)		**b**	8.2 (6.4)		**b**	49.7 (36.5)		**b**	58.4 (43,.8)		**b**	165.8 (141.1)		**b**	121.3 (113.5)		**B**
Stemflow	**Before clear-cutting**	275.4 (209.8)		**c**	43.2 (30.5)		**c**	118.2 (58.0)		**c**	149.9 (69.3)		**c**	30.2 (231.5)		**c**	161.8 (174.3)		**C**

		DOC		
		× (SD)	TEST	test
Rainfall	**Before clear-cutting**	4.6 (3.5)	A	**a**
	After clear-cutting	4.2 (2.1)	A	/
Throughfall	**Before clear-cutting**	19.7 (32.2)		**b**
Stemflow	**Before clear-cutting**	69.9 (31.7)		**c**

TEST: comparison of data before and after felling (a different letter indicates a significant difference at 5%).
test: comparison of concentrations between rainfall, throughfall and stemflow solutions, before and after felling separately (a different letter indicates a significant difference at 5%).
× (SD): mean (square deviation).

Table III. Mean composition of gravitational solutions collected at four levels in the soil for the period before clear-cutting [from July 1992 to November 1998] and after clear-cutting [from November 1998 to December 2001] (data in $\mu mol_c L^{-1}$ except Si expressed in mole L^{-1}, pH in pH units and DOC in mg L^{-1}).

		pH			F^-			$H_2PO_4^-$			SO_4^{2-}			Fe^{2+}			H_4SIO_4		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test
Forest floor	Before clear-cutting	4.7 (0.5)	A	c	04 (0.6)	B	a	19.7 (15.5)	A	b	128 (89)	A	a	13.4 (7.7)	A	b	64 (34)	BB	a
	After clear-cutting		B	**b**	0.,0 (0.2)	A	**a**	36.5 (79.1)	B	**b**	54 (24)	A	**a**	15.6 (7.6)	A	**b**	51 (26)	A	**a**
15 cm depth	Before clear-cutting	4.4 (0.4)	A	a	1.0 (1.3)	B	a	0.9 (3.0)	A	a	171 (78)	A	a	4.0 (3.6)	A	a	146 (68)	BB	c
	After clear-cutting	5.2 (0.6)	B	**b**	0.0 (0.3)	A	**a**	0.3 (0.8)	A	**a**	84 (52)	A	**b**	3.3 (2.8)	A	**a**	79 (46)	A	**b**
30 cm depth	Before clear-cutting	4.6 (0.5)	A	bc	1.0 (1.3)	B	a	0.5 (3.0)	A	a	137 (58)	A	a	3.1 (3.3)	B	a	112 (44)	A	b
	After clear-cutting	4.7 (0.3)	A	**a**	0.0 (0.0)	A	**a**	0.1 (0.3)	A	**a**	126 (34)	B	**c**	1.5 (1.1)	A	**a**	121 (34)	A	**c**
60 cm depth	Before clear-cutting	4.5 (0.3)	A	ab	2.8 (5.9)	A	b	0.2 (1.3)	A	a	184 (121)	A	a	2.2 (2.5)	A	a	63 (32)	A	a
	After clear-cutting	4.7 (0.4)	B	**a**	2.3 (2.4)	A	**b**	4.4 (9.4)	B	**a**	195 (70)	B	**d**	1.1 (1.8)	A	**a**	79 (30)	A	**b**
120 cm depthA	Before clear-cutting	4.4 (0.3)	A	ab	9.3 (3.7)	A	c	0.3 (1.3)	A	a	379 (125)	A	b	1.6 (2.8)	A	a	135 (43)	A	c
	after clear-cutting	4.6 (0.1)	A	**a**	4.9 (2.4)	B	**c**	0.1 (0.3)	A	**a**	326 (38)	B	**e**	1.5 (3.6)	A	**a**	126 (38)	A	**c**

		Mn^{2+}			Mg^{2+}			Ca^{2+}			Al^{3+}			Na^+			K^+		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test
Forest floor	Before clear-cutting	48 (33)	B	c	97 (58)	B	bc	292 (164)	B	c	67 (33)	A	a	48.6 (31.3)	B	a	161 (76)	B	c
	After clear-cutting	18 (11)	A	**b**	60 (23)	A	**bc**	198 (100)	A	**c**	69 (49)	A	**a**	29.2 (13.9)	A	**a**	123 (63)	A	**b**
15 cm depth	Before clear-cutting	35 (24)	B	b	103 (53)	B	c	320 (168)	B	c	298 (164)	B	c	48.5 (24.0)	B	a	138 (101)	A	b
	After clear-cutting	7 (8)	A	**a**	30 (26)	A	**a**	72 (58)	A	**a**	127 (114)	A	**b**	30.3 (18.0)	A	**a**	122 (148)	A	**b**
30 cm depth	before clear-cutting	29 (18)	B	ab	80 (41)	B	bc	171 (85)	B	b	190 (125)	B	b	42.9 (20.3)	A	a	74 (57)	B	a
	After clear-cutting	13 (10)	A	**b**	51 (31)	A	**bc**	99 (50)	A	**ab**	106 (74)	A	**ab**	33.6 (14.9)	A	**ab**	42 (27)	A	**a**
60 cm depth	Before clear-cutting	21 (10)	A	ab	61 (27)	A	a	111 (56)	A	a	157 (83)	B	b	43.6 (18.2)	A	a	67 (42)	A	a
	After clear-cutting	16 (10)	A	**b**	50 (34)	A	**bc**	84 (49)	A	**ab**	110 (76)	A	**ab**	43.5 (23.5)	A	**b**	59 (31)	A	**a**
120 cm depth	Before clear-cutting	61 (23)	B	d	103 (49)	B	bc	219 (61)	B	b	396 (310)	B	d	67.7 (33.4)	A	b	67 (25)	B	a
	After clear-cutting	27 (8)	A	**c**	54 (17)	A	**bc**	128 (35)	A	**b**	140 (52)	A	**b**	56.9 (19.1)	A	**c**	49 (11)	A	**a**

		NO_3^-			NH_4^+			DOC		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test
Forest floor	Before clear-cutting	376 (272)	B	b	134 (112)	B	b	55.5 (25.2)	B	a
	After clear-cutting	178 (136)	A	**a**	65 (535)	A	**c**	42.1 (14.1)	A	**a**
15 cm depth	Before clear-cutting	618 (434)	B	c	42 (59)	B	a	22.0 (12.3)	A	c
	After clear-cutting	85 (203)	A	**a**	9 (8)	A	**a**	20.4 (16.5)	A	**d**
30 cm depth	Before clear-cutting	370 (342)	B	b	29 (43)	B	a	16.2 (13.7)	B	b
	After clear-cutting	121 (170)	A	**a**	9 (7)	A	**a**	11.1 (6.4)	A	**c**
60 cm depth	Before clear-cutting	178 (138)	A	a	34 (42)	A	a	17.6 (24.7)	B	bc
	After clear-cutting	167 (202)	A	**a**	39 (61)	A	**b**	6.3 (3.1)	A	**bc**
120 cm depth	Before clear-cutting	563 (498)	B	c	24 (35)	B	a	5.1 (2.4)	B	a
	After clear-cutting	111 (98)	A	**a**	8 (6)	A	**a**	3.3 (0.8)	A	**ab**

TEST: comparison of data before and after felling (a different letter indicates a significant difference at 5%).
test: comparison of concentrations between soil level, before and after felling separately (a different letter indicates a significant difference at 5%).
× (SD): mean (square deviation).

Table IV. Correlation coefficient (r) between the concentration of anions and cations in the gravitational (A) and capillary (B) solutions for the period before clear-cutting.

A- Gravitational solutions

		Mg^{2+}	Al^{3+}	Ca^{2+}
SO_4^{2-}	r_{FF}	0.87	0.35	0.82
	$r_{15\ cm}$	0.60	0.53	0.57
	$r_{30\ cm}$	–0.06	–0.14	–0.01
	$r_{60\ cm}$	0.04	0.33	–0.06
	$r_{120\ cm}$	0.10	0.30	0.18
NO_3^-	r_{FF}	0.83	0.23	0.86
	$r_{15\ cm}$	0.86	0.85	0.93
	$r_{30\ cm}$	0.71	0.70	0.73
	$r_{60\ cm}$	0.77	0.57	0.74
	$r_{120\ cm}$	0.95	0.95	0.87

B- Capillary solutions

		Mg^{2+}	Al^{3+}	Na^+	Ca^{2+}
SO_4^{2-}	$r_{15\ cm}$	0.48	0.05		0.44
	$r_{30\ cm}$	-0.16	–0.14		–0.01
	$r_{60\ cm}$	-0.63	–0.39		–0.64
	$r_{120\ cm}$	0.80	0.28		0.67
NO_3^-	$r_{15\ cm}$	0.77	0.84		0.71
	$r_{30\ cm}$	0.76	0.71		0.38
	$r_{60\ cm}$	0.85	0.73		0.86
	$r_{120\ cm}$	0.70	0.35		0.13
Cl^-	$r_{15\ cm}$			0.67	
	$r_{30\ cm}$			0.80	
	$r_{60\ cm}$			0.57	
	$r_{120\ cm}$			0.98	

167 µmol$_c$ L^{-1} at 30 cm and increasing again in the deeper layers (193 µmol$_c$ L^{-1} at 60 cm and 211 µmol$_c$ L^{-1}at 120 cm). The deficit of the ionic balance can be related to the DOC, requiring a charge of organic carbon varying from 7 to 10 µmol$_c$ per mg of C from forest-floor to 60 cm. At 120 cm, the charge of C should be of 41 µmol$_c$ per mg of C for equilibrating the deficit. That indicates that another problem occurred, probably with the element speciation. For cations, ZTL solutions were dominated by Al^{3+} (from 157 µmol$_c$ L^{-1}at 60 cm to 395 µmol$_c$ L^{-1} at 120 cm) and Ca^{2+} (from 111 µmol$_c$ L^{-1} at 60 cm to 320 µmol$_c$ L^{-1} at 15 cm), except under forest-floor, where the dominant cations were Ca^{2+} (292 µmol$_c$ L^{-1}) and NH_4^+ (134 µmol$_c$ L^{-1}). Anions were dominated by NO_3^- (from 376 µmol$_c$ L^{-1} under forest-floor to 563 µmol$_c$ L^{-1} at 120 cm) and SO_4^{2-} (from 128 µmol$_c$ L^{-1} under forest-floor to 379 µmol$_c$ L^{-1} at 120 cm). The solution pH ranges from 4.7 under forest-floor to 4.4 at 120 cm. Correlations between concentrations of SO_4^{2-} and cations were generally weaker than between nitrate and cations as presented in Table IV.

The general trend for concentration changes was as follows: concentrations increased from the forest floor to 15 cm, decreased at a depth of 30 and 60 cm, and then increased again. The seasonal cycles clearly appeared on graphs particularly on the upper layers of the soil, but failed to be significant due to the inter-annual climate shifting.

After the clear-cutting, the concentration of the majority of elements in gravitational solutions dramatically decreased in the upper layers of the soil (FF, –15 and –30 cm). Changes were less noticeable at 60 cm (being only significant for Al^{3+} and DOC), but the decrease was again significant at 120 cm. The pH and the total ion concentration varied in an opposite way. A strongly significant decrease occurred for NO_3^- at 15 cm (from 618 to 85 µmol$_c$ L^{-1}) and at 30 cm (from 370 to 121 µmol$_c$ L^{-1}). That large decrease was associated with a decrease in cations like Ca^{2+} (from 320 to 72 µmol$_c$ L^{-1} at 15 cm and from 170 to 96 µmol$_c$ L^{-1} at 30 cm), Al^{3+} (from 298 to 127 µmol$_c$ L^{-1}at 15 cm and from 189 to 106 µmol$_c$ L^{-1} at 30 cm), and Mg^{2+} (from 103 to 30 µmol$_c$ L^{-1}at 15 cm and from 80 to 51 µmol$_c$ L^{-1}at 30 cm). At a depth of 60 cm, no significant decrease was observed except for Al^{3+} (from 157 to 110 µmol$_c$ L^{-1}) and DOC. At 120 cm, the decrease in NO_3^-, Ca^{2+}, Al^{3+} and Mg^{2+} was larger (minus 80% for NO_3^-, minus 60% for Al^{3+}, and minus 40% for Mg^{2+}). Figure 4 illustrates the changes after the clear-cutting for major anions and cations at various soil depths.

Strongly significant correlations were observed between the concentration of nitrate and cations for all the soil layers. Correlations between concentrations of SO_4^{2-} and cations were generally lower and failed to be significant from a depth of 30 cm. Cl^- was more especially correlated with Na^+ (Tab. IV).

Seasonality tended to disappear after the clear-cutting especially in the soil upper layers. The decrease in concentration was drastic, immediate and durable at 15 and 30 cm during the 3-year-observation period.

3.2.4.2. Capillary solutions

Before the clear-cutting, the cationic charge of the capillary solutions varied from 672 µmol$_c$ L^{-1}at 15 cm to 752 µmol$_c$ L^{-1} at 120 cm (Tab. V). The ionic balance was characterized by an excess of anions in the upper layers but an excess of cations at 60 cm and 120 cm. Two reasons can explain the deficit in cations of -47 µmol$_c$ L^{-1}at 15 cm, –2.6 µmol$_c$ L^{-1} at 30 cm, and its excess of + 6.6 µmol$_c$ L^{-1} at 60 cm, and +29 µmol$_c$ L^{-1} at 120 cm: (i) Al – the dominant cation – was not completely in the Al^{3+} form in that acidic solution (from 4.3 to 4.7) [24],

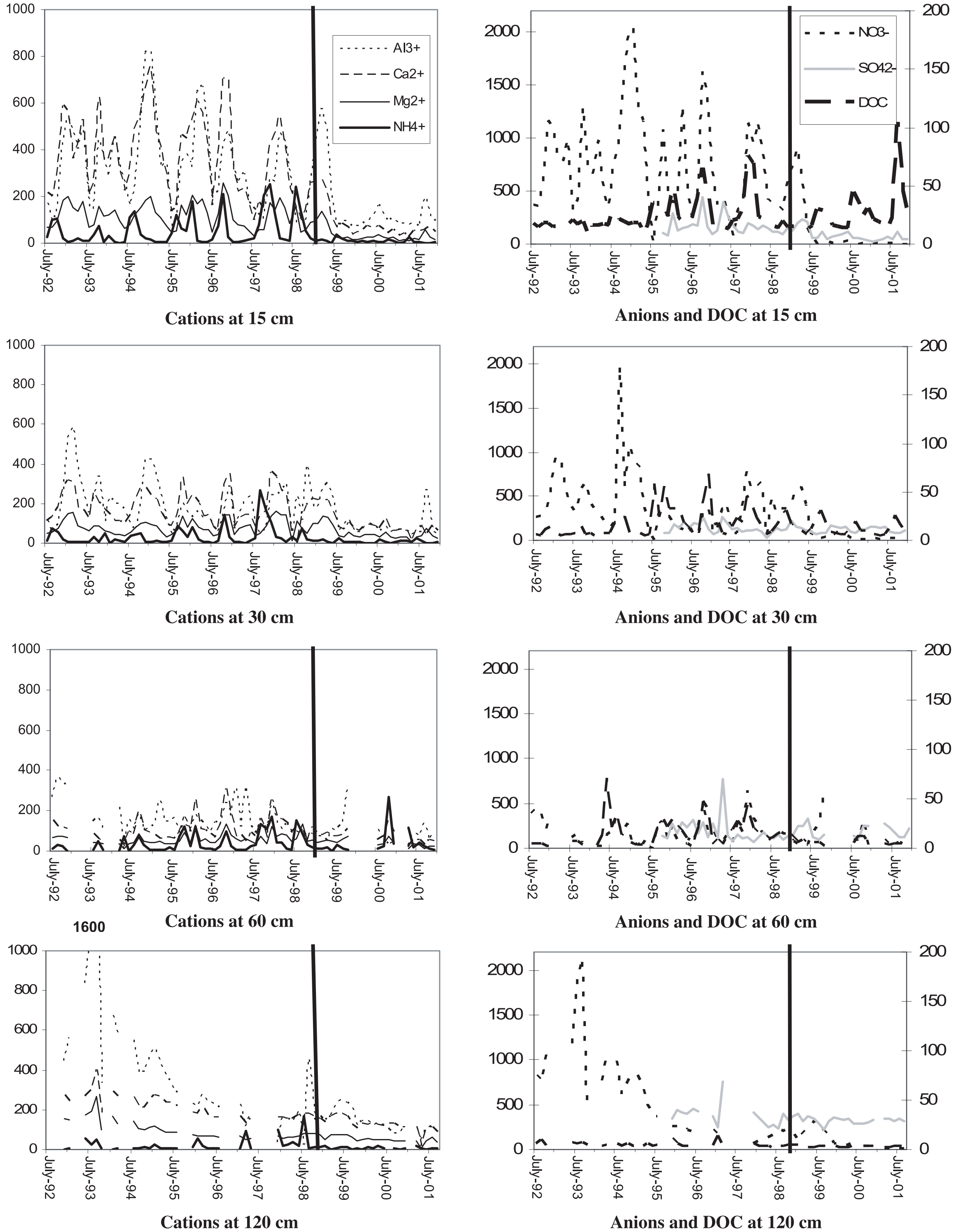

Figure 4. Changes in concentrations of gravitational solutions at 15, 30, 60 and 120 cm depth (cations: Al^{3+}, Ca^{2+}, Mg^{2+}, NH_4^+, and anions: NO_3^-, SO_4^{2-}: left scale, DOC: right scale), before and after clear-cutting (vertical line) (data in $\mu mol_c L^{-1}$, except DOC in mg L^{-1}).

Table V. Mean composition of capillary solutions collected at four levels in the soil for the period before clear-cutting (June 1997 to November 1998) and after the clear-cutting (from November 1998 to December 2001) (data in $\mu mol_c L^{-1}$ except Si expressed in mole L^{-1} and pH in pH Units).

		pH			**F^-**			**$H_2PO_4^-$**			**SO_4^{2-}**			**Fe^{2+}**		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test
15 cm depth	**Before clear-cutting**	4.6 (0.4)	A	a	2.9 (3.2)	A	a	0.0 (0.0)	A	a	304 (337)	B	a	1.9 (1.8)	A	a
	After clear-cutting	4.6 (0.1)	A	**b**	2.2 (1.7)	A	**a**	0.0 (0.0)	A	**a**	184 (50)	A	**a**	1.3 (1.9)	A	**b**
30 cm depth	**Before clear-cutting**	4.5 (0.3)	A	a	3.0 (1.5)	A	a	0.0 (0.0)	A	a	290 (49)	A	a	1.2 (0.9)	B	a
	After clear-cutting	4.6 (0.1)	A	**b**	3.0 (1.7)	A	**a**	0.0 (0.1)	A	**a**	248 (75)	A	**b**	0.6 (0.4)	A	**a**
60 cm depth	**Before clear-cutting**	4.3 (0.2)	A	a	5.8 (1.7)	A	a	0.0 (0.0)	A	a	217 (59)	A	a	12.3 (0.7)	B	a
	After clear-cutting	4.6 (0.1)	B	**b**	5.3 (1.7)	A	**b**	0.1 (0.3)	A	**a**	285 (61)	B	**c**	0.8 (0.6)	A	**a**
120 cm depth	**Before clear-cutting**	4.8 (0.9)	A	a	18.1 (7.4)	A	b	1.4 (4.3)	A	a	434 (282)	A	a	0.9 (0.5)	A	a
	After clear-cutting	4.5 (0.2)	A	**a**	21.1 (5.6)	A	**c**	0.0 (0.0)	A	**a**	412 (76)	A	**d**	0.7 (0.4)	A	**a**

		H_4SIO_4			**Mn^{2+}**			**Mg^{2+}**			**Ca^{2+}**			**Al^{3+}**		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test
15 cm depth	**Before clear-cutting**	174 (36)	A	a	30 (18)	B	a	96 (45)	B	a	139 (77)	B	a	149 (95)	A	a
	After clear-cutting	156 (30)	A	**a**	17 (8)	A	**a**	63 (35)	A	**a**	93 (49)	A	**c**	202 (115)	A	**a**
30 cm depth	**Before clear-cutting**	172 (46)	B	a	18 (4)	A	a	82 (15)	A	a	65 (23)	B	a	187 (94)	A	a
	After clear-cutting	144 (25)	A	**a**	15 (5)	A	**a**	72 (25)	A	**a**	44 (15)	A	**a**	206 (86)	A	**a**
60 cm depth	**Before clear-cutting**	173 (67)	B	a	45 (35)	B	a	114 (49)	B	a	104 (30)	B	a	293 (72)	B	b
	After clear-cutting	145 (24)	A	**a**	23 (5)	A	**b**	68 (16)	A	**a**	68 (14)	A	**b**	203 (58)	A	**a**
120 cm depth	**Before clear-cutting**	180 (78)	A	a	38 (49)	A	a	141 (97)	B	a	109 (128)	A	a	240 (126)	A	ab
	After clear-cutting	153 (30)	A	**a**	27 (7)	A	**c**	92 (18)	A	**b**	74 (14)	A	**b**	274 (76)	A	**b**

		Na^+			**K^+**			**NO_3^-**			**NH_4^+**		
		× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test	× (SD)	TEST	test
15 cm depth	**Before clear-cutting**	144 (125)	B	a	53 (53)	B	ab	205 (147)	A	a	24.5 (28.9)	B	a
	After clear-cutting	61 (35)	A	**a**	26 (12)	A	**a**	242 (253)	A	**a**	12.3 (7.2)	[illegible]	**a**
30 cm depth	**Before clear-cutting**	171 (72)	B	a	23 (6)	A	a	76 (72)	A	a	8.1 (4.5)	A	a
	After clear-cutting	73 (46)	A	**ab**	52 (203)	A	**a**	178 (167)	A	**a**	10.6 (7.4)	A	**a**
60 cm depth	**Before clear-cutting**	106 (58)	B	a	73 (24)	B	b	398 (151)	B	b	9.5 (6.8)	A	a
	After clear-cutting	67 (29)	A	**ab**	54 (12)	A	**a**	191 (123)	A	**a**	13.4 (10.5)	A	**a**
120 cm depth	**Before clear-cutting**	277 (370)	B	a	79 (49)	A	b	181 (137)	A	a	12.7 (8.3)	A	a
	After clear-cutting	84 (38)	A	**b**	67 (22)	A	**a**	203 (124)	A	**a**	14.5 (134.0)	A	**a**

TEST : comparison of data before and after felling (a different letter indicates a significant difference at 5%).
test : comparison of concentrations between soil level, before and after felling separately (a different letter indicates a significant difference at 5%).
× (SD): mean (square deviation).

and (ii) the accuracy of the analysis, in which a deficit of less than 5% of the ionic charge was measured, can be challenged.

Anions in the capillary solutions were dominated by SO_4^{2-} at 15 cm (304 μmol_c L^{-1}), 30 cm (290 μmol_c L^{-1}), and 120 cm (434 μmol_c L^{-1}), and by NO_3^- (398 μmol_c L^{-1}) at 60 cm. The secondary anion varied with the depth, being NO_3^- at 15 cm, Cl^- at 30 and 120 cm and SO_4^{2-} at 120 cm. For cations, Al^{3+} dominated with values of 149 μmol_c L^{-1} at 15 cm, 187 μmol_c L^{-1} at 30 cm, 293 μmol_c L^{-1}at 60 cm and 276 μmol_c L^{-1} at 120 cm. The secondary dominant cation varied with soil layer (Ca^{2+} at 15 cm, Na^+ at 30 cm, Mg^{2+} at 60 and 120 cm).

Correlations between concentration of SO_4^{2-} and cations were generally lower than between nitrate and cations; Cl^- was more especially correlated with Na^+.

It was not possible to identify seasonal trends before the clear-cutting because observations were only made during one year.

After the clear-cutting, the tendency was towards an increase in the concentration of Al^{3+} (+52 μmol_c L^{-1} at 15 cm and +19 μmol_c L^{-1} at 30 cm) and NO_3^- (+37 μmol_c L^{-1} at 15 cm and +102 μmol_c L^{-1} at 30 cm) in the soil upper layers, but not at 30 and 120 cm. The concentration of other major elements tended to decrease e.g. for Ca^{2+} the decrease amounted to 47 μmol_c L^{-1}at 15 cm, 20 μmol_c L^{-1}at 30 cm, 37 μmol_c L^{-1} at 60 cm and 35 μmol_c L^{-1}at 120 cm. The pH variation was not significant except at 60 cm (+0.3 pH unit). Figure 5 illustrates the changes after the clear-cutting for major anions and cations at different soil depths.

3.3. Water and element fluxes

3.3.1. Water flux

After the clear-cutting, the water flux could increase from 365 to 541 or 628 mm at 60 cm and 120 cm depending on the scenarios (Tab. VI). That was due to several causes: (i) an effective increase in soil moisture observed with the soil moisture monitoring (+2.4, +0.5, +0.4 and +1.3% volumetric humidity, respectively at 15, 30, 60 and 120 cm), (ii) an extra mean annual rainfall of 100 mm after the clear-cutting due to an inter-annual variability, (iii) the supposedly specific behaviour of ground vegetation, and, (iv) a different rooting distribution in the soil, between trees and ground vegetation.

The drainage excess associated with the 100 mm extra rainfall after the cutting was estimated at about 77 mm from a statistic relation between rainfall and drainage before the clear-felling ($R^2 = 0,97$ at 60 or 120 cm for 6 data from 1992 to 1998). In relative terms, the extra drainage after the clear-cutting represents 48% of the value before the felling at a depth of 60 cm and of 60% at 120 cm for scenario 1. For scenario 2, the values were +72% at 60 cm and +86% at 120 cm. The part of drainage due to an extra rainfall represented about 20% of that amount.

3.3.2. Atmospheric deposition

Wet deposition (WD) amounted to 8.2, 0.6, 1.6, 3.2 and 0.6 kg $ha^{-1}year^{-1}$ respectively for N, P, K, Ca and Mg. After the felling, it increased proportionally to the increase in rainfall (100 mm). Before the clear-cutting, dry deposition (DD) was high, usually of the same magnitude as WD for elements other than N (57% in NH_4^+-N form). DD amounted to 12.4, 0.7, 2.1, 5.6 and 0.6 kg ha^{-1} $year^{-1}$, respectively for N, P, K, Ca and Mg [49]. After the clear-cutting, DD was nil for all the elements. Moreover, the whole flux from crown leaching was nil (it represented 10.2 kg ha^{-1} $year^{-1}$ for K). However the increase in the ground vegetation biomass after the clear-cutting may have intercepted some air pollutants, but no measurements were made.

3.3.3. Fluxes in gravitational solutions

According to scenario 1, at 60 cm, after the clear-cutting, and for the major elements, the drainage increased by about 12.4, 6.1, 3.2, 1.4, 1.1 kg ha^{-1} $year^{-1}$ and by 15.4, 7.8, 4.4, 1.8 and 0.4 kg ha^{-1} $year^{-1}$ for scenario 2, respectively for N, K, Ca, Mg and Al. Losses of P were always negligible but sulphate losses strongly increased up to +61 and +73 kg ha^{-1} $year^{-1}$ respectively for scenarios 1 and 2 (Tab. VIIA).

At 120 cm, an increase in K was observed by 1 kg ha^{-1} $year^{-1}$ for scenario 1 and by 2.4 kg ha^{-1} $year^{-1}$ for scenario 2. A decrease was observed for the majority of elements, with respectively –15.8, –0.2 and –3.2 for scenario 1 and –17, 2, –0.7 and –4.2 kg ha^{-1} $year^{-1}$ for scenario 2 for N, Mg and Al. Ca changes were positive for scenario 1 (+0.7) but negative for scenario 2 (-1.1). Again P losses were negligible but sulphate losses strongly increased after the felling (+70 and +59 kg ha^{-1} $year^{-1}$ respectively for scenarios 1 and 2) (Tab. VIIB).

In relative values, at 120 cm, it represented a change of –64, +12, –8 and –18 % for N, K, Ca and Mg respectively for scenario 1 and of –59, +29, +5 and –5 % for N, K, Ca and Mg respectively for scenario 2.

4. DISCUSSION

4.1. Comparison of the solution phases before the clear-cutting

The results generally showed that, in the soil upper layers, gravitational solutions tended to be more concentrated than solutions collected by porous-cup lysimeters. The contrary was observed at 60 cm. At 120 cm, gravitational waters once more became the most concentrated in NO_3^- and Ca^{2+}. We have already discussed that behaviour in a study where strongly fixed solutions extracted by centrifugation had also been studied in the same site. The main conclusions were [48]:

– Gravitational solutions have a short residence time in the soil (some days for the rapidly transferred part). Their

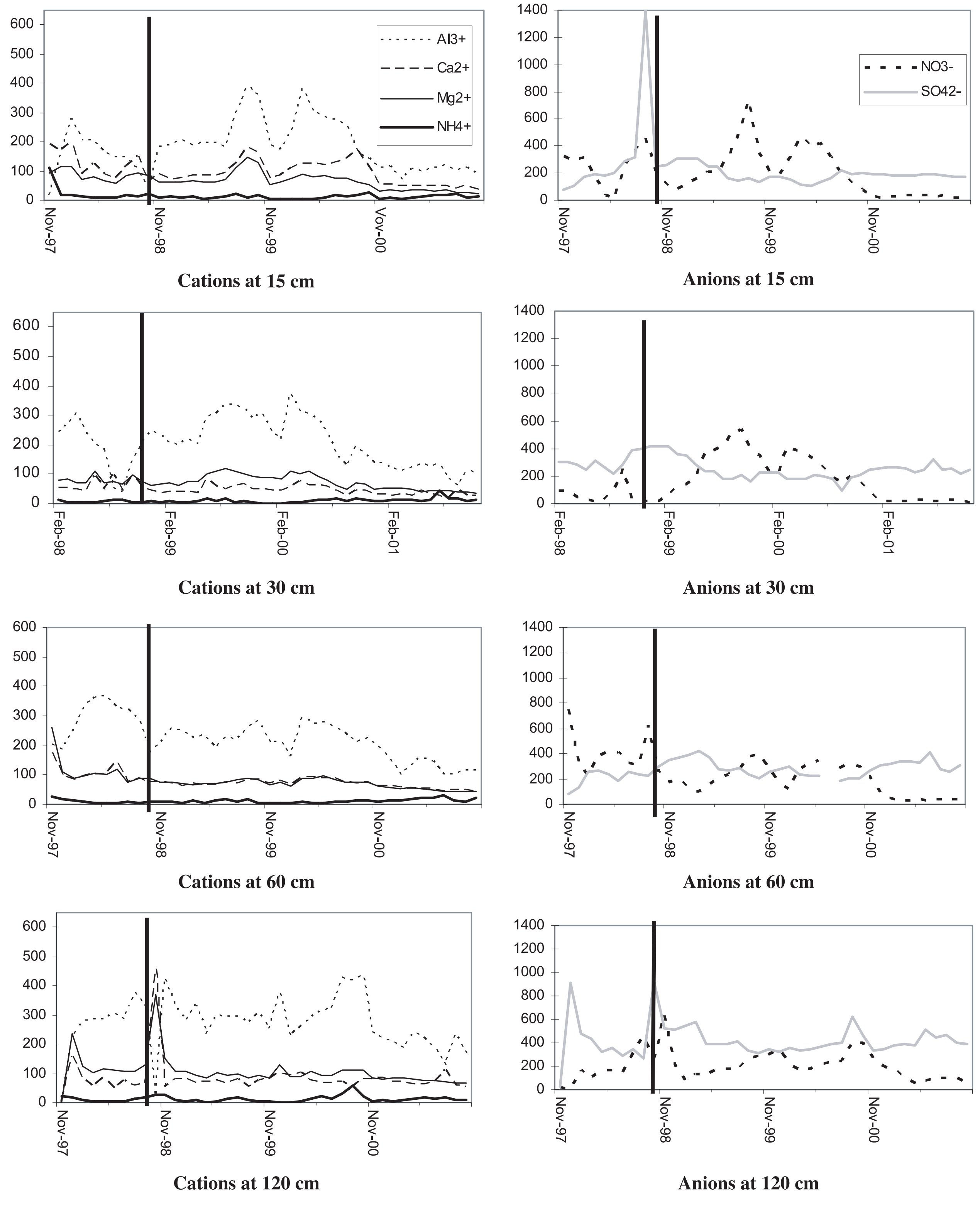

Figure 5. Changes in concentrations of capillary solutions at 15, 30, 60 and 120 cm depth (cations: Al^{3+}, Ca^{2+}, Mg^{2+}, NH_4^+, and anions: NO_3^-, SO_4^{2-}), before and after clear-cutting (vertical line) (data in $\mu mol_c L^{-1}$).

Table VI. Water fluxes calculated by the model before and after clear-cutting according to the selected scenarios.

		Rainfall	Tree canopy interception	Tree throughfall	Tree stemflow		Drainage at 15 cm	Drainage at 30 cm	Drainage at 60 cm	Drainage at 120 cm
Before clear-cutting	Total (mm)	964	217	725	22		566	463	365	338
	Range	818–1194	187–264	609–918	19–28		441–771	334–680	242–592	221–556
After clear-cutting	Total (mm)	1065	0	0	0	***Scenario*** **1**	***729***	***600***	***541***	***541***
						Scenario 2	774	667	628	628
	Range	948–1153					***606–819***	***471–690***	***431–636***	***431–636***
							649–860	537–758	497–724	497–727

Scenario 1: transpiration of ground vegetation = 40 % PET, interception of rainfall by ground vegetation = 10% rainfall, direct soil evaporation = 25% of PET.

Scenario 2: transpiration of ground vegetation = 35 % PET, interception of rainfall by ground vegetation = 5% rainfall, direct soil evaporation = 20% of PET.

chemical composition mainly reflects rapid reactions such as the displacement of soluble products or less soluble products physically displaced, and/or ion exchange reactions. The uptake by vegetation is thought to be limited in this phase.

– The strongly fixed solutions mainly reflected production processes, mineralization of organic matter and mineral weathering, as the role of vegetation should be limited in this phase, in the present mountainous site. Their residence time is long and their concentration is high, depending on the amount of weatherable minerals still present in the soil [37, 48].
– The weekly fixed solutions, collected by porous cup lysimeters, behave in an intermediate way. Their mean residence time in the soil is longer than that of the gravitational solutions. The flux of production by mineral weathering or organic matter mineralization is higher than before, but the utpake by the roots is also higher: the two source and sink functions are difficult to distinguish from each other. Only some elements can be used as indicators of the production reactions, because they are weak or not taken up by plants e.g. C (residue of decomposition), Al (tracer of ion exchange and weathering reactions), SO_4^{2-} (tracer of adsorption-desorption reactions), and Si secondarily.

The physical parameters of the solute transfer complicated the system e.g. preferential flow, lateral flow, displacement by translatory flow. The latter was regarded as a possible way of explaining the homogenisation of the chemistry of solution phases in the soil deeper layers [50]. The lateral flow could explain the high concentrations in nitrates observed at 120 cm in the gravitational waters, but high time variations and a general decrease in concentration with time can lead to assume that the installation of ZTL initially disturbed the observations. Nevertheless, it is unusual that this effect should not begin immediately after setting on lysimeters, and that it should last for at least 4 years.

4.2. Effects of clear-cutting on soil solutions and ecosystem functioning

In the soil upper layers, ZTL and TL solutions changed in different ways: the concentration of elements in ZTL solutions strongly decreased while the concentration of the same elements in the TL solutions tended to increase weakly during this period. In the deeper layers, ZTL solutions did not change much at 60 cm but their concentration tended to decrease at 120 cm. TL solutions did not change much either in the deeper layers.

After the cutting, the soil solutions were observed for three years, and no temporal tendency appeared to determine how long the impact of the cutting would last. It can be said that no changes occurred during the third year, but no extrapolation can be made presently.

The way in which the solutions behaved after the clear-cutting was not the expected one. In the present situation, the hypothesis of an increase in drainage losses was based on:

(i) Potentially intense mineralization and nitrification rates in an ecosystem where nitrification was high in the previous plantation in spite of the acidity of the soil [31]. The hypothesis was that previous agricultural occupation of the land could explain this behaviour in reference to the work done in another area [34].
(ii) The changes of physical parameters the after clear-cutting e.g. increase in soil temperature and moisture, and the rather large amount of organic matter in the forest-floor were supposed to favour an increase in the mineralization and nitrification rates [9, 63].
(iii) The disruption between production and consumption of nutrients, which would lead to a huge amount of nitrates not taken up by vegetation.
(iv) The extreme mobility of nitrate in this soil type, as previously observed by Ranger et al. [48].

As the hypothesis was not verified, it is necessary to describe each type of change in the ecosystem to try to understand the specific behaviour observed for drainage waters:

– Changes in the inputs:
  - Dry deposition which represented between 50 and 60% of the total atmospheric deposition, according to each element, became negligible after the clear-cutting. Trees were eliminated and the ground vegetation was not supposed to have an efficient effect on pollutant capture. Wet deposition was not changed qualitatively but due to the higher mean annual precipitation in the

Table VII. a. Fluxes of elements drained at 60 cm depth on the Douglas-fir stand, before and after clear-cutting (data in kg ha^{-1}year^{-1}). b. Fluxes of elements drained at 120 cm depth on the Douglas-fir stand, before and after clear-cutting (data in kg ha^{-1}year^{-1}).

(A) at 60 cm	Flux of elements before cutting	Flux of elements after cutting Scenario 1	Flux of elements after cutting Scenario 2	Difference (after-before cutting) Scenario 1	Difference (after-before cutting) Scenario 2
F^-	0.1	0.3	0.3	+0.2	+0.2
Cl^-	3.6	11.2	12.5	+7.6	+8.9
$H_2PO_4^{2-}$	0	0	0	0	0
SO_4^{2-}	21.8	83.2	94.3	+61.4	+72.5
Fe^{2+}	0.1	0.1	0.1	0	0
H_4SiO_4	7.8	12.1	13.9	+4.3	+6.1
Mn^{2+}	1.8	2.8	3.2	+1	+1.4
Mg^{2+}	2.3	3.7	4.1	+1.4	+1.8
Ca^{2+}	6.3	9.5	10.7	+3.2	+4.4
Al^{3+}	5.6	6	6.7	+0.4	+1.1
Na^+	3.4	6.2	7	+2.8	+3.6
K^+	6.1	12.2	13.9	+6.1	+7.8
NO_3^-	6.5	15.4	17.2	+8.9	+10.7
NH_4^+	0.7	4.2	5.4	+3.5	+4.7
DOC	30.7	28.6	36.6	-2.1	+5.9
(B) at 120 cm					
F^-	0.2	1	1.1	+0.8	+0.9
Cl^-	2.3	10.6	12	+8.3	+9.7
$H_2PO_4^{2-}$	0	0	0	0	0
SO_4^{2-}	20.7	79.6	90.4	+58.9	+69.7
Fe^{2+}	0.1	0.1	0.1	0	0
H_4SiO_4	12.1	17.7	20.4	+5.6	+8.3
Mn^{2+}	5.5	3.8	4.3	-1.7	-1.2
Mg^{2+}	4	3.3	3.8	-0.7	-0.2
Ca^{2+}	14	12.9	14.7	-1.1	+0.7
Al^{3+}	11.1	6.9	7.9	-4.2	-3.2
Na^+	4.4	6.9	7.8	+2.5	+3.4
K^+	8.4	9.4	10.8	+1	+2.4
NO_3^-	25.9	9	10.4	-16.9	-15.5
NH_4^+	0.8	0.5	0.5	-0.3	-0.3
DOC	16	16.1	18.4	+0.1	+2.4

For scenarios see table V.

period after the cutting, it increased quantitatively by about 10% for all the elements.

- Mineral weathering should increase moderately due to changes in soil climate. Ezzaïm [22] quantified the weathering flux at 7.5, 0.9 and 1 kg ha^{-1} year^{-1} respectively for K, Ca and Mg before the clear-felling. The 20 % increase proposed had no great effect on this flux due to its initial rate.

– Internal transformations of the ecosystem:

- Stems were exported. Slashes were windrowed and, so, eliminated from the site where a new plantation was made. Neither any mineralization nor any microbial immobilization fluxes originated from them. Only roots left on site would progressively decompose.
- Tree litter-fall stopped after the clear-cutting: it represented 31.9, 2.2, 7.3, 21.5 and 2.3 kg ha^{-1} year^{-1}, respectively for N, P, K, Ca and Mg [51]. The contribution to litter-fall of the ground vegetation was not measured. Its nutrient content before the clear-cutting was 43.0, 2.6, 31.2, 15.6 and 5.9 kg ha^{-1}, respectively for N, P, K, Ca and Mg Nevertheless, if one considers that the pre-existent vegetation, mainly constituted

of two-yearly plants, had equilibrated production and mortality, and that translocation before senescence was about 50 % for N, the current N-litter-fall would not overpass one third of what was observed for trees.

- Tree crown leaching disappeared. It was especially relevant for K cycle in a Douglas-fir stand (about 10 kg.ha^{-1}.year^{-1}) [43]. The present contribution of the ground vegetation was not known.
- Forest-floor, which represented 16.6 t of C ha^{-1}, was largely decomposed after the stand was cut off. In 2001, only 6.4 t of C ha^{-1} remained. About 420 kg ha^{-1} of organic-N (representing about 3.5% of the initial stock) disappeared, but soil monitoring showed that only about one half of it would have been mineralized; the other part would have been transferred to mineral soil as organic-C particles by meso-fauna [51].
- The organic nitrogen mineralization and nitrification rates, which were measured in situ for a period of 6 years before and 2 years after the cutting, following Raison's method [45], decreased after the clear-felling [33].
- The biomass of micro-organisms was measured in the site before and after clearing following the fumigation-extraction method [14]. Before the clear-cutting, the microbial biomass was of 330 mg C kg^{-1} for the 0–10 cm soil layer, in 1995, 1996, 1997 [31]. In April 1999, the microbial biomass was 400 mg C kg^{-1} for the 0–5 cm layer; it then increased to 1300 mg C kg^{-1} from October 1999 to October 2000, and then returned to its previous level. In the 5–10 and 10–15 cm layers the microbial biomass soared in April 1999 to 1800 and 1300 mg C kg^{-1} respectively, but then returned to its the initial level of about 400 mg C kg^{-1} as early as the following month [56]. The limited changes in the microbial biomass did not seem sufficient to explain the durable modifications observed in the soil solutions for 3 years following the cutting.
- Ammonium and above all nitrate fixation in soil were not supposed to play any role in this soil type [26].

– Changes in the outputs:
  - The uptake by vegetation was strongly modified after the clear-cutting. The uptake of the Douglas-fir stand disappeared (36, 3.3, 19.3, 25, 3.4 kg ha^{-1} for N, P, K, Ca and Mg respectively) [51]. Changes due to the ground vegetation concerned the increment of uptake linked to its immediate development after the clear-cutting (+23, +1.4, +16.8, +8.4 and +3.1 kg. ha^{-1} for N, P, K, Ca and Mg respectively). The effect of the ground vegetation, whose biomass increased by about 70% in 1999, stabilized for the following two years. The uptake of ground vegetation mainly concerned the weakly fixed phase of soil solution.
  - The water flux drained moderately increased as indicated by the continuous monitoring of soil moisture.
  - Denitrification was not measured. It probably explained a small part of N-fluxes before the clear-cutting in this site with high mineralization and nitrification rates. The sandy loam texture led to a rather well drained soil. Only few works reported high rates of denitrification after clear-cutting. Ineson et al. [29] measured fluxes of 10 to 40 kg N ha^{-1} yr^{-1} after the clear-felling of a Sitka spruce stand in a peaty-gley soil in Scotland. The behaviour of gravitational solutions with very low and constant concentrations seemed to eliminate a control of their nitrate content by denitrification because this flux is usually strongly discontinued. Changes in soil moisture (less than 2%) could increase the denitrification rate, but would remain too limited to modify drastically the denitrification process in the present ecosystem [5].

As a whole, after the clear-cutting, changes in the composition of weakly-fixed solutions were related to specific processes studied in the site e.g. mineralization, mineral weathering (only quantified before the cutting), uptake by vegetation and microbial immobilization. The tendency was that all these fluxes tended to increase except for the mineralization, leading to a rather stable chemical composition.

Changes in the gravitational solutions after the clear-cutting reflected two different main processes: (i) the decrease in the inputs to the soil e.g. deposition, crown leaching and litter-fall, and (ii) the exchange with the fixed solution. The decrease in the inputs, due to an elimination of tree crown interactions with rain, directly affected the gravitational flux, which had a short residence. The decrease in the mineralization and nitrification rates limited the residual amount of available nitrates after vegetation uptake and microbial immobilization. The mechanical consequence was that the net proton production decreased, and the exchange of elements between strongly and weakly fixed solutions then between weakly fixed and free solutions would decrease too. After the clear-felling, these two processes would lead to a strong and immediate decrease in the gravitational solutions in the soil upper layers where exchange between phases of soil solutions are far more limited than in deeper layers. In the deeper soil layers, the physics of the transfer, involving a translatory flow, led to a homogenization between the two types of solutions, and to more limited changes in the chemistry of gravitational solutions.

It was necessary to take into account all the fluxes and the behaviour of both gravitational and weakly-fixed solutions after the clear-felling to explain the ecosystem behaviour in that particular case. The classical processes invoked, like denitrification or microbial immobilization, failed to be key processes in the present situation, whereas N-mineralization and nitrification truly were.

The observations made led to the conclusion that carbon and nitrogen cycles were the main driving forces of the ecosystem changes. Nevertheless, significant sulphate losses tended to indicate that sulphate adsorption was no more in equilibrium after clear-cutting. Atmospheric deposits were 12.7 kg SO_4^{2-}-S before cutting including 7.2 kg from dry deposition [41]. Desorption of sulphate is an acidification process [11] which could contribute to soil changes and drainage losses after clear-felling. Nevertheless, sulphate adsorption is not an immediate and totally reversible mechanism [53]. In the present situation, changes in solutions did not confirm the acidification process associated to sulphate desorption and could suggest an organic origin of the sulphate from SOM mineralization.

The element budget reasonably explained the solution behaviour, but nevertheless, the observations failed to explain why the key process of mineralization and nitrification was reduced after the felling. The only mechanism that could explain the observations was the relationship between the vegetation and micro-organisms. The hypothesis is that Douglas-fir stimulated the activity of nitrifyers, and that eliminating the trees would result in a decrease in their activity. It was found in some situations that ground flora controlled nitrifyers. Several examples demonstrated that the eradication of herbs or their replacement by tree vegetation led to an immediate nitrification development [1, 8, 42]. In the present case, the ground flora did not change in terms of species before and after the clear-cutting. Thus, it cannot be involved in the changes in the control of nitrifyers. In another site, where different forest species were planted in a previous broadleaved native forest in the Morvan region (France), a high nitrification rate appeared in the soil under Douglas-fir, compared to Norway spruce or Nordmann-fir. This site was never cultivated and no ground flora existed in this dense 30-year-old stand [52]. The inhibition of nitrifyers by forest species was reported long ago, but the confounding effects between soil acidity, chemical mediation (allelopathy), competition between micro-organisms according to the stage of development of the ecosystem have not been clarified [39]. Rice and Pankoli [55] reported that climax ecosystems inhibited nitrification without identifying the underlying process. Occurrence of nitrification in acidic soils was reported long ago [60] as being the fact of autotrophic microbes adapted to acidic conditions [19, 30] or of specific heterotrophic organisms [19]. Nevertheless, no report was found concerning stimulation of nitrification by forest species, especially in very acid soils. This hypothesis still needs to be tested.

4.3. Effect of clear-cutting on losses by drainage

Element losses associated with drainage waters increased after the trees were clear-cut, at 60 cm but not at 120 cm. At 60 cm, this rise originated in an increase in the water flux, but not in changes in the chemistry of gravitational water. At 120 cm, the water flux increased but the concentrations decreased. As said before, at this depth, and during the 6-year-observation before the clear-cutting, the trend in the water chemistry was somewhat singular. For this reason, it is easier to discuss the results at 60 cm. An additional difficulty with the diachronic approach used in this study was that the years following the cutting were wetter than before (77 mm of extra drainage). The diachronic approach was very interesting because it allowed us to follow continuously the soil solutions strictly in the same conditions apart from the treatment, but climate hazards cannot be kept under control [15].

At both depths, the scenarios selected to integrate the interaction of the ground vegetation in order to calculate the water budget had no large effects on fluxes of elements, because it did not change anything on chemistry.

At 60 cm, the extra mean annual drainage after the clear-cutting was high in relative values (3 times for N, and 2 times for K, Ca and Mg) but rather low in absolute value (15 kg of N, 8 kg of K, 4.4 kg of Ca and 1.8 kg of Mg for the less conservative scenario). Extra drainage of Al was about 1 kg, indicating that the potential negative impact on surface waters was limited.

In this site, the clear-cutting had no real adverse effect on drainage for the duration of the observations (3 years after treatment). No trend was clear enough to extrapolate the data but as the new stand develops quickly, the stand effect should rapidly overpass the clear-cutting effect.

The harvest of the present plantation was made without significant physical soil degradations, which explained part of the observations, but only part of them. The land was previously occupied by agriculture, and, expertise would have predicted a rather large increase in nitrates and nutrient cations in solutions. This was not verified in this site, where the previous mineralization and nitrification rates were high [32]. If the key process is that Douglas-fir controlled the activity of nitrifyers, one could expect that the ecosystem behaviour after the clear-felling would depend again on the tree species and on the ground vegetation.

This means that recommendations to managers for limiting the adverse effects of clear-cutting on plantations ecosystem were more complex than previously expected. Effects would depend on the site, on previous land occupation, on the intensity of soil disturbance, and on the vegetation (both trees and ground vegetation). Concerning the impact of clear-cutting on ecosystem losses, data from the literature is rather contrasted. This is probably due to the fact that the role of vegetation and its interaction with site conditions and management are still very poorly understood.

5. CONCLUSION

The hypothesis tested, i.e. that clear-cutting would increase the drainage losses in the Douglas-fir experimental site of Vauxrenard, where the mineralization and nitrification rates where high before the clear-felling, was not verified. On the contrary, concentration of the gravitational solutions dropped down in the upper soil layer and did not change in the deep soil layers. The concentration of solutions collected by porous cup-lysimeters behaved differently, with a small increase in the upper layers but no significant changes in the deeper layers.

The study showed that the impact of clear-felling, where very few disturbance was applied to the soil and where the tree vegetation seemed to stimulate the soil nitrifyers, led to moderate nutrient losses by drainage.

The study of the processes underlying this result is of paramount interest to try to identify the key-processes that are responsible for such an unexpected behaviour in this site classified as potentially responsive. Information brought by both types of soil solutions was of great interest.

Nitrification was a key process for losses and the hypothesis that Douglas-fir stimulated the activity of nitrifyers was the only one that could explain that behaviour. Of course the hypothesis needs checking, but we observed the same behaviour in another experimental site [52]. Allelopathy was thought to be a potential mechanism [64] but this remains to be clarified. New tools of molecular biology will be helpful to identify the type of micro-organisms and their activity.

Acknowledgements: This research was founded by the GIP-ECOFOR and by the GESSOL project of the Ministry in charge of Environment.

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