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Uranium leaching during short term application of pit-water on a carbonate containing soil in the Mendoza province of Argentina

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Abstract

Excess water from an open pit uranium (U) mine outside the city of San Rafel, Mendoza province, Argentina, contains on an average 3500 µg l^{-1} U, for which clean up by soil passage is under consideration. The objective of the investigation reported here was to quantify the amount of U retained during a soil passage of the pit water. A model experiment with 30 cm long soil columns was conducted grown with *Agropyron elongatum* L. in order to investigate U leaching during short term pit water application. During the 6 week experiment the passage through the 30 cm soil columns retained most (> 99 %) of the 11042 µg U in total applied with the irrigation water. Plant growth decreased the leachate volumes between 30-65 % through evapotranspiration which caused an increase of the U concentrations in the leachates, but reduced the total discharge of U from the columns. Phosphate application improved plant growth and by this reduced U discharge.

Although the results indicate that passing through a soil matrix is a very efficient measure to clean up U contaminated waters this method is not acceptable to be applied outside of strictly closed circuit systems, unless accepted U values are met. The U concentrations in the leachates with >50 - < 200 µg l^{-1} U were far above any reccommended critical values for drinking water (9-30 µg l^{-1} U), but also as the U charged to the soil remains highly available for plant uptake it becomes a threat for the food chain or other compartments of the natural environment.

Key words: absorption, contamination, environmental protection, leaching, mining, pollution, soil, uranium, wastes

Zusammenfassung

Uranaustrag während kurzzeitiger Verregnung von Tagebauabwässern auf einem karbonathaltigen Boden der argentinischen Provinz Mendoza

Abwasser des Uran (U)-Tagebaus bei San Rafel, Provinz Mendoza in Argentinien, enthält im Mittel 3500 µg l^{-1} U, welches durch Verregnung und Bodenpassage weitgehend entfernt werden soll. Ziel der Forschungsarbeit war es, die Menge an U zu quantifizieren, die bei Verregnung im Boden zurückgehalten werden. In einem Modellexperiment mit 30 cm langen Bodensäulen, bewachsen mit Agropyron, wurde der Austrag von U bei kurzzeitiger Beregnung mit Abwasser des Tagebaus untersucht. Während der sechs Wochen Versuchsdauer wurden bei der Passage durch die 30 cm Bodensäulen > 99 % der insgesamt mit Beregnungswasser aufgebrachten 11042 µg U zurückgehalten. Pflanzenbewuchs reduzierte die Mengen an Perkolationswasser durch Evapotranspiration um 30-65 % wodurch gleichzeitig die U-Konzentrationen im Sickerwasser anstiegen, die insgesamt ausgetragene Menge an U jedoch abnahm. Auf dem natürlich P-armen Substrat stimulierte die Zufuhr von Phosphat die Produktion von Biomasse, weshalb hier die geringsten Uranausträge gemessen wurden.

Die Ergebnisse zeigen zwar, dass die Passage durch Böden U aus Tagebauabwässern weitgehend entfernen kann, dennoch erscheint aus Gründen des Schutzes von Gewässern und Böden das Verfahren nur für geschlossene Systeme geeignet. Mit >50 - < 200 µg l^{-1} U lagen die Konzentrationen der Sickerwässer in diesen Untersuchungen weit über den empfohlenen Richtwerten für Trinkwasser (9-30 µg l^{-1} U). Bedenklich ist aber auch die Tatsache, dass das im Boden angereicherte U von Pflanzen leicht aufgenommen werden und so in die Nahrungskette gelangen kann.

Schlüsselwörter: Abraum, Absorption, Auswaschung, Bergbau, Boden, Kontamination, Umweltschutz, Uran

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1 Introduction

The San Rafael open pit uranium mine and processing facility (CMFSR) is an 800 ha site lying in the Sierra Pintada, 30 km SE of the city of San Rafael (34.6°S, 68.4°W, elevation 227 m) in the province of Mendoza, Argentina. Due to an almost 10 year relapse in the mining activities, its open-air pits have received a flow of water which has not been used in any of the processes, filling their maximum capacity.

A restarting of the activities is currently under way, and the pits need to be emptied in order to continue mining processes. Besides other heavy metals this pit water contains naturally 3500 μg l^{-1} U, and can therefore not be disposed in the surrounding water courses. Among the different treatment and disposal alternatives, also irrigation of the water is under consideration. At present, a small area of unaltered soil inside the mining complex is available for a pit-water irrigation field experiment, based on the proposition that the soil will retain the contaminants. Field irrigation with U containing waters has been studied and put to practice in Australia with varying results (Riley, 1992; Noller and Zhou, 1992), but the soils involved differed from the high carbonate content, slightly alkaline pH characteristics of the CMFSR soil.

Uranium mobility (as uranyl) in soils may be limited by formation of complexes with low solubility, and by adsorption, preferably to Fe and Mn oxy-hydroxides, organic matter (OM) and clays (Ribera et al., 1996). In coarse-textured soils with a low OM content, major ions applied through irrigation are expected to be readily mobile in the soil profile but the amount of U that may be involved can be immobilized even by poor sorption capacity soils (Willet and Bond, 1992). In soils of neutral to alkaline pH, carbonate presence induces the formation of stable uranyl-carbonate complexes. These highly soluble complexes are mainly neutral and negatively charged, minimizing adsorption to soil particles and enhancing U mobility. (Elless and Lee, 1998; Finch and Murakami, 1999). In contrast, the presence of phosphates, may induce precipitation of highly insoluble uranyl-phosphate complexes (Buck et al., 1996; Finch and Murakami, 1999). The low solubility and high stability of U-P complexes have led to several studies on the remediation of contaminated water and soils by U immobilization with inorganic phosphates, mainly apatites (Conca et al., 2000; Seaman et al., 2001).

Larrea tridentata, the most common desert shrub in the southwest of the United States, has been found growing in heavy metal contaminated areas, and subsequently studied

Fig. 1:
Water filled pit at the San Rafael uranium mine and processing 30 km SE of the city of San Rafael (34.6°S, 68.4°W, elevation 227 m) in the province of Mendoza, Argentina

and recognized as a heavy metal accumulator (Gardea-Torresdey et al., 1996). Furthermore, its inactivated biomass has been found able to bind heavy metals from contaminated waters in biosorption experiments (Gardea-Torresdey et al., 1997). However, no reports are available on the effect of direct application of *Larrea spp*. tissue to the soil for limiting contaminant migration. *Larrea spp*. (mainly *L. nitida* and *L. divaricata)* also thrive in most of the unaltered areas of the CMFSR and its surroundings. Appart from the positive visual effect, vegetation presence is generally favorable for reducing horizontal migration of contaminants caused by wind and water erosion of soils (Entry et al., 1997). Establishment of vegetation can also reduce water percolation due to an increase in water demand through evapotranspiration (hydraulic control), thus limiting heavy metal leaching. Furthermore, plants have the potentiality of reducing U contamination by extraction through roots (phytoextraction) (Dushenkov, 2003). However, it has been pointed out that plant presence may favor Zn and Cd mobility (Banks et al., 1994; Zhu et al., 1999), probably through an increase in metal solubility due to complexation with organic compounds exuded by plant roots and rhizosphere microorganisms. In this way, the risk of contaminant leaching through the soil may be increased.

In the present soil column experiment, the leaching of U during a short term application of pit-water to a coarse textured, low OM, high-carbonate soil was determined: a) with addition of processed *Larrea spp*. tissue as amendment, b) with addition of triple superphosphate fertilizer as amendment, and c) without soil amendments. Also the effect of plant presence was evaluated.

2 Materials and methods

2.1 Experimental design and statistical analyses

The experimental design was 2 x 3 factorial completely randomized with 5 replicates. The factors were *plant* (two levels: plants and no plants), *amendment* (three levels: no amendment, *Larrea spp*. tissue (Lr) and triple superphosphate fertilizer (TSP)). The resultant 6 treatments and their abbreviations were: No plants, no amendment (NN); no plants, Lr (NL); no plants, TSP (NP); plants, no amendment (PN); plants, Lr (PL) and plants, TSP (PP).

Statistical analysis of the data involved analysis of variance (ANOVA) using the General Lineal Model (GLM) and analysis of regression using the Regression Procedure (REG) of the Statistical Analysis System (SAS Vs. 8, 1999).

2.2 Soil and amendments

The upper 20 cm layer of soil was sampled from an unaltered area of the mine. The CMFSR is situated in a mountain area where the soil is mostly rock and has not been surveyed in detail for its classification. However, soil maps classify some soils in the area as an association of Typic Paleorthids (70 %) and Typic Torrifluvents (30 %) (Hudson et al., 1990). Some soil properties are presented in table 1. The soil was air dried, passed through a 2 mm sieve, and homogenized prior to loading the columns. Commercial TSP was finely ground and used as amendment in the NP and PP treatments. Twigs with leaves were cut from *Larrea spp*. plants from uncontaminated areas around the CMFSR. They were oven dried, finely ground and homogenized before use as amendment in the NL and PL treatments. Water directly sampled from the pit was used for irrigation. Some properties of the pit-water and the amendments are also presented in table 1. Twice throughout the experiment (on days 9 and 26), 140 mg of reactive grade ammonium nitrate were dissolved in the water and applied to every column to provide nitrogen for plant growth, equivalent to 12.1 mg kg^{-1} N in the soil.

Table 1:
Selected properties of soil, amendments (TSP = Triple superphosphate, Lr = *Larrea spp*. tissue) and pit water used in the experiment

	Soil	TSP	Lr	Pit-water
U (µg g^{-1})	2.4 †	84.0	0.1	3500 (µg L^{-1})
Total P (µg g^{-1})	641	2 10^5		
$P_{available}$ (µg g^{-1})	0.98	2 10^5		
N (%)	0.06		1.05	
$PH_{(KCl)}$	7.7			7.2
$C_{organic}$ (%)	0.36			
Carbonates (%)	6			
δap ‡ (g cm$^{3-1}$)	1.42			
Texture	Loamy sand			

† Within baseline values for soils in San Rafael
‡ δap = apparent density

2.3 Column preparation

30 soil columns were built out of 10 cm diameter polyvinylchloride (PVC) pipes, cut to 33 cm length (figure 2). Each pipe was fitted with a PVC end cap with a 5 cm diameter hole bored in it to allow for the liquids to leach. The end cap also held taut a piece of voile cloth filter, to prevent loss of fines. 318 g of acid-washed sand were added initially to each column, as a filtering bed, covering the bottom 2 cm of the columns. Over the sand, an initial 3311 g portion of soil were packed, equivalent to a depth of 27 cm. The soil was added in various steps, slightly tapping the columns and humidifying after each addition. The columns were then randomly selected to receive each of the 6 treatments. A final 376 g portion of soil, equivalent to a 3 cm layer, was thoroughly mixed with 88.2 mg TSP, 1000 mg Lr, or shaken without amendment, and added to each column, giving concentrations of

Fig. 2:
View of the column experiment for the investigation of Uranium leaching during short term application of pit-water on a high-carbonate-content soil in the Mendoza province of Argentina

47 mg kg soil^{-1} P and 2660 mg kg soil^{-1} Lr in this last 3 cm layers.

A 1 cm border was left on top of each column. *Agropyron elongatum* seeds were planted in separate trays with acid-washed sand. After 16 days cultivation on Hoagland solution, 30 seedlings were transplanted into each of the packed soil columns. The finished columns were placed in wooden supports specially built for the purpose, with a hollowed base, under which a plastic funnel fitted to a plastic 0.5 L bottle collected the leachate. The experiment was carried out in a growth chamber providing a 12 hour light period. Temperature was not controlled, but an air conditioning system and fans were used to prevent temperature from rising over 30 °C.

2.4 Irrigation and U analyses

Before initiating pit-water irrigation, distilled water was applied to all columns until field capacity was reached and the first drops of gravitational water started to leach. Day one of the experiment commenced on first application of pit-water. Irrigation was manually applied employing controlled slow flow from a burette, ensuring that all columns received the same daily volume of water. Pit-water was applied in an amount enough to keep all columns slightly over field capacity, obtaining a minimum volume of leachate every day. At the end of every week, leachates were collected, their volumes measured and compared against the week's amount of pit-water applied. Aliquots were taken and acidified with nitric acid prior to total U measurement by means of laser fluorescence employing a Scintrex UA-3 analyzer.

3 Results and discussion

3.1 Leachate volumes

Following the irrigation criteria established for this experiment, irrigation volumes had to be increased weekly to compensate plant growth and to maintain field capacity in the columns with plants in order to receive a minimum amount of leachates (table 2).

Table 2:
Weekly irrigated and leached volumes and ANOVA for the variable leachate volume

	Irrigated volume (ml week^{-1})					
	Week 1	*Week 2*	*Week 3*	*Week 4*	*Week 5*	*Week 6*
All treatments	300	400	425	550	650	830
	Leachate volume (ml week^{-1})					
Treatment	*Week 1*	*Week 2*	*Week 3*	*Week 4*	*Week 5*	*Week 6*
NN	139	138	172	270	405	587
NL	123	109	167	257	386	570
NP	132	135	174	271	404	586
PN	96	67	105	116	193	315
PL	94	76	100	121	197	317
PP	93	65	81	45	59	96
Average						
No plants	131 a	127 a	171 a	266	398	581
Plants	94 b	69 b	95 b	94	150	243
No amendment	117	102	138	193	299	451
Lr	108	92	133	189	291	443
TSP	112	100	127	158	154	341
	Probability of F					
Plant	***	***	***	***	***	***
Amendment	-	-	-	**	***	***
Plant x Amend.	-	-	-	***	***	***
CV (%)	10.2	19.3	11.0	10.4	9.4	6.9

Treatments: NN = No plants, no amendment; NL = No plants, processed Larrea spp. tissue; NP = No plants, triple perphosphate; PN = Plants, no amendment; PL = Plants, processed Larrea spp. tissue and PP = Plants, triple superphosphate.
Means in columns followed by the same letter are not significantly different at $p \le 0.05$ level (Fisher´s LSD test)
Probability of F (- = $p > 0.05$; * = $p < 0.05$; ** <= $p < 0.01$; *** = $p < 0.001$)

There were no interactions between the leachates collected from treatments with plants and amendments within the first three weeks of the experiment. Columns with plants leached less volume than unvegetated ones, but there was no difference in leachate volumes due to the different amendments (table 2). The results from the weeks four, five and six, however, revealed interactions between the leached amounts from treatments with plants and the different amendments. Therefore comparisons of the three amending levels were performed within each of the two plant levels. No differences were found among the amendments applied to the columns without plants. Where plants were growing, the PP treatments leached less volume than PN and PL. This was also observed in week three, but the difference failed to be statistically significant. The effect of plant growth was also compared within each amendment level, revealing that *Agropyron elongatum* considerably reduced the leachate volumes, regardless of the amendment (table 3). This reduction effect was again highest in the PP treatment. The reduction in leachate volume by plants is considered due to transpiration by the vegetation because evaporation should have been the same among all columns due to identical light and temperature conditions. Visually plant growth in PP was higher than in PN and PL treatments throughout the experiment, which was confirmed by the dry matter yields obtained at the end of the experiment (data not shown). Reason for this was that the plants in the PP treatment benefited from the additional P supply because the soil used is naturally low in plant available P. This again resulted in lower leachate volumes due to a higher plant biomass production and consequently to increased transpiration. However, reduced plant growth may have occurred in treatments PS and PL due to U toxicity. U present in calcareous soils is expected to be not only mobile but also highly available to plants, favoring U phytotoxicity in greenhouse experiments (Shahandeh and Hossner, 2002; Lamas, 2005; Meyer et al., 2004). P addition has been found to alleviate toxic effects of U, probably due to complexation, reduced solubility and consequently a decrease of U availability to plants (Ebbs et al., 1998). Therefore the addition of TSP in the PP treatment may have prevented, or at least reduced, plant growth inhibition by U contamination.

Results of linear regression analyses revealed a close significant positive linear relationship between leachate volumes and irrigated volumes for all treatments except for PP (table 3). This indicates that virtually all increase in leachate volume can be explained by increasing volumes irrigated. Treatments NN, NL and NP had very similar regression models, suggesting that there was no specific effects caused by the amendments. The models for PN and PL were also very similar inbetween themselves, and the resulting R^2 was only slightly lower than those in the no-plant treatments. This suggests that part of the irrigated water was used by plants, and also that each increase in irrigation volume exceeded any increasing need of the plants for water. The leachate volume in PP showed no relationship to the irrigated volumes, but being the treatment with highest plant growth, this suggests that the weekly increases in irrigation were almost completely used by the plants.

Table 3:
Regression equations for the relationship between irrigated volume (X) and leachate volume (Y) throughout the 6 week experiment

Treatment	Regression	R^2 (%)
NN	Y = 0.913 X - 195	95.6
NL	Y = 0.912 X - 211	95.4
NP	Y = 0.920 X - 200	96.2
PN	Y = 0.441 X - 83.4	86.0
PL	Y = 0.447 X - 84.2	88.2
PP	Y = 0.001 X + 72.4	0.0

Treatments: NN = No plants, no amendment; NL = No plants, processed *Larrea spp*. tissue; NP = No plants, triple perphosphate; PN = Plants, no amendment; PL = Plants, processed *Larrea spp*. tissue and PP = Plants, triple superphosphate

3.2 Uranium concentration in leachates

For all of the treatments U concentration in the leachates was much lower than in the applied pit water (table 4). There were no interactions between plant growth and amendments except for week 5. Throughout the whole experiment, leachates from columns with plant growth had higher U concentrations, except in the first week. Zhu et al. (1999) observed in column experiments with up to 1 year duration, that Cd and Zn concentrations in leachates were significantly higher from vegetated columns than from unvegetated ones for most of the time. From this they concluded that the presence of growing plants increased the mobility of these heavy metals in the substrate. Banks et al (1994) also obtained a similar result for Zn in a short-term greenhouse experiment. This effect might also be at least partly responsible for increased U concentrations in the leachates from treatments with plant growth..

Effects of the factor “amendment” was significant only for weeks 1 and 2, where Lr increased U concentrations compared to TSP and no amendment (table 4). Lr also produced higher U concentrations in week 3 for both, unvegetated and vegetated columns, and for all the following weeks in unvegetated columns only, though all these differences failed to be statistically significant. TSP yielded the highest U concentrations in the leachates from columns with plant growth in weeks 4 and 6, while Lr application produced higher U concentrations than the no amendment treatment, but also these effects failed statistical significance (table 4). As discussed by Kim (1991), trace elements, including U, are proportionally higher in groundwaters whose colloids have higher dissolved organic carbon contents, implying bondage and transport of trace elements on humic substances. Almas et al. (1999) found that soil application of organic matter in the form of pig manure increased Cd and Zn concentration in the mobile fractions extracted from that soil, as well as in the soil solution collected. Lr mixing with the soil may be enhancing U mobilization due to the organic source of the amendment. In this experiment TSP may also have been responsible for increased U concentrations, but it acted more likely through an increase in plant biomass, enhancing plant effects on U concentrations, since no incidence of TSP in U concentrations of unvegetated columns was observed.

Comparing the leachate volumes with the U concentrations throughout the weeks, some negative relationship between these two variables is suggested for the columns without plant growth. The correlation coefficients for the results from the treatments NN, NL and NP revealed to be negative (-0.811, -0.893 and -0.872). In contrast the treatments PN, PL and PP showed no significant correlation at all. Simple linear regression analyses showed similar results with volume of irrigation and amount of U applied as independent variables (data not shown). In the regression analyses the data for week 1 were excluded, since part of the leachate collected during this week was probably a low U concentration mixture of distilled water applied before irrigation with U, and the pit-water. U concentration in the applied pit water was constant, so decreasing U concentration with increasing leachate volumes (and increasing amounts of water and U applications) indicates that soil in the unvegetated columns, even without amendments, retained most of the applied U until the end of the experiment. This soil characteristic should apply for vegetated columns too, where only a positive correlation could have suggested otherwise. Plant growth, however, favored leaching of U, probably in relation to growth evolution through the weeks, so that no relationship between U concentration and any of the other variables mentioned above was observed.

Table 4:
Weekly irrigated volume, applied U and U concentration in leachates. ANOVA results for U concentration in leachates

	Irrigated volume (ml week^{-1})					
	Week 1	*Week 2*	*Week 3*	*Week 4*	*Week 5*	*Week 6*
All treatments	300	400	425	550	650	830
	Applied U (µg week^{-1})					
	Week 1	*Week 2*	*Week 3*	*Week 4*	*Week 5*	*Week 6*
All treatments	1050	1400	1487	1925	2275	2905
	U concentration in leachates (µg U L^{-1})					
Treatment	*Week 1*	*Week 2*	*Week 3*	*Week 4*	*Week 5*	*Week 6*
NN	46	83	68	47	28	25
NL	84	132	88	77	43	30
NP	53	82	76	53	24	21
PN	59	116	140	140	102	101
PL	98	165	157	156	122	155
PP	53	134	146	186	188	149
Average						
No plants	61	99 b	77 b	59 b	32	25 b
Plants	70	207 a	148 a	161 a	137	135 a
No amendment	52 b	99 b	104	93	65	63
Lr	91 a	148 a	122	116	82	92
TSP	53 b	108 b	111	119	106	85
	Probability of F					
Plant	-	*	***	***	***	***
Amendment	***	*	-	-	-	-
Plant x Amend.	-	-	-	-	**	-
CV (%)	21	27	37	27	33	40

Treatments: NN = No plants, no amendment; NL = No plants, processed Larrea spp. tissue; NP = No plants, triple perphosphate; PN = Plants, no amendment; PL = Plants, processed Larrea spp. tissue and PP = Plants, triple superphosphate.
Means in columns followed by the same letter are not significantly different at p ≤ 0.05 level (Fisher´s LSD test)
Probability of F (- = $p > 0.05$; * = $p < 0.05$; ** <= $p < 0.01$; *** = $p < 0.001$)

3.3 Leached uranium

U applied by pit-water irrigation leached from the soil columns from the beginning of the experiment on (table 5). The amount of U leached was obtained as the product of leachate volume and U concentration in the leachates. During the first five weeks, no interactions were found between the factors "plant" and "amendment". Plant growth increased the amount of U leached in week 5 and also in week 6 within the treatments without amendment and Lr addition, but not within TSP. As discussed previously, plant growth favored the increase of U concentration in the leachates, probably as a result of mobilisation through root activity. But plant growth reduced also the leachate volumes, so that the amount of U leached did not differ from that with no plants, where the U concentration was reduced through the weeks, and leachate volume increased (tables 2 and 4). By week 5, U concentrations in the columns without plant growth was low enough to yield significant differences in U leached from columns with plant growth. By week 6 the leachate volumes in PN and PL were high enough to yield significant differences within the columns with plants for the treatments without amendment and Lr.

Although throughout the experiment U leached was different among the amendment levels, significant effects could only be found in weeks 1, 4, 5 in columns without and only in week 6 for the columns with plant growth. In all cases, and irrespective of statistical significance, Lr application increased the amount of U leached, both in

Table 5:
Amount and ANOVA for uranium leached weekly

Treatment	Leached U (µg week^{-1}) *Week 1*	*Week 2*	*Week 3*	*Week 4*	*Week 5*	*Week 6*
NN	6	11	12	13	11	15
NL	10	14	15	20	16	17
NP	7	11	13	14	10	12
PN	6	8	15	16	19	31
PL	9	13	17	18	23	48
PP	5	8	12	8	11	14
Average						
No plants	8	12	13	16	12 a	15
Plants	7	10	15	14	18 b	31
No amendment	6 b	9	13	14 b	15 b	23
Lr	9 a	13	16	19 a	19 a	32
TSP	6 b	9	12	11 b	10 c	13
	Probability of F					
Plant	-	-	-	-	**	***
Amendment	***	-	-	**	***	***
Plant x Amend.	-	-	-	-	-	***
CV (%)	22	35	40	29	28	32

Treatments: NN = No plants, no amendment; NL = No plants, processed Larrea spp. tissue; NP = No plants, triple perphosphate; PN = Plants, no amendment; PL = Plants, processed Larrea spp. tissue and PP = Plants, triple superphosphate.
Means in columns followed by the same letter are not significantly different at $p \leq 0.05$ level (Fisher´s LSD test)
Probability of F ($- = p > 0.05$; $* = p < 0.05$; $** <= p < 0.01$; $*** = p < 0.001$)

columns with and without plants (table 5). This increase was a result of higher U concentrations in the leachate, while this amendment had no effect at all in leachate volume. Differences within amendment levels also applied to TSP where the reduction of the amounts of U leached went below those obtained with no amendment in week 5, and within vegetated columns in week 6 and Week 4 (not significant). These differences are mainly caused by the lowest leachate volumes in PP.

4 Conclusions

During short-term irrigation of two months, the passage through a 30 cm long column of an unamended and unvegetated soil with 6 % total carbonates reduced the U concentration of 3500 µg U L^{-1} in pit water from an U mining operation to between 25 and 83 µg U l^{-1} in the leachate. By the end of the experiment (after 6 weeks) the soil was still able to retain U.

Although this results indicate that passing through a soil matrix is a very efficient measure to clean up U contaminated waters this method is not acceptable to be applied outside of strictly closed circuit systems. The U concentrations in the leachates with >50 - < 200 µg l^{-1} U were far above any reccommended critical values for drinking water (9-30 µg l^{-1} U, WHO, 2004; EPA, 2000), but also the U charged to the soil remains highly available for plant uptake (Lamas, 2005; Meyer et al., 2004) and is therefore a persisting thread for the food chain or other compartments of the natural environment. Only previous treatment of the pit water to lower U concentration below critical values would make irrigation acceptable in open systems, allowing for even lower concentration in leachates with minimal charge to the soil.

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