Effects of long term raw pig slurry inputs on nutrient and metal contamination of tropical volcanogenic soils, Uvée Island (South Pacific)

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HIGHLIGHTS

- Pig slurry dispersal induces heavy metals contamination in mixed calcareous soils.
- In impacted mixed calcareous soils phosphorus and heavy metals are exchangeable.
- In impacted pure ferralitic soils phosphorus and most heavy metals are immobilized.
- Family pig breeding and pig slurry dispersal should be restricted on coastal soils.

GRAPHICAL ABSTRACT

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ABSTRACT

In small Polynesian islands, family pig breeding is usually conducted without recovery of pig slurry. Raw pig slurry is spread onto the soil without any treatment. So far, most of the studies were carried out in temperate climate and for industrial digested pig slurry applications on agricultural lands. In the present case study, conducted in Uvée Island, the aim is to determine if long term application of raw pig slurry on tropical soils, naturally rich in heavy metals has a significant influence on elements concentrations and mobility. Two types of tropical soils and two pig breeding systems, pig enclosure on small concrete pens or pig enclosure in large land pens, were investigated. Here we demonstrate that raw pig slurry inputs on soils can lead to an increase of total nitrogen and phosphorus content with high Contamination Factors. The Pollution Load Index values (1.3; 5.3; 2.5; 2.3) were indicative of multi-heavy metals pollution (Fe, Mn, Al, Cu, Zn, Cr and Ni) in mixed calcareous soils of the coastal area and they are exchangeable while they are immobilized or less mobile in inland pure ferralitic soils. For mixed calcareous soils of the coastal area, family pig breeding represents a drainage risk of soluble species (phosphorus, inorganic nitrogen, Fe, Mn, Al, Cu, Zn, Cr and Ni). For inland ferralitic soils, family pig breeding is more compatible with a sustainable management of the environment in Uvée Island and by extension in volcanic tropical islands with respect to the investigated chemical elements.

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1. Introduction

In the Polynesian culture, pig breeding plays a major role in the political-economic and socio-religious system since social events (wedding, funerals, communion...) are underlined by pig meals cooked

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in traditional earth ovens. Thus inhabitants have a pig breeding near their family houses. As a result, porcine density is significant for these small islands. Uvéa Island, a tropical island in the Territory of Wallis and Futuna Islands, has been chosen as a case study: in 2002, the number of pigs was estimated to be 2 to 15 per inhabitant in Wallis and Futuna (Fediavesky and Angus, 2002). The absence of traffic and industrial activities and the limited urbanization guarantees that Pig Slurry (PS) input was the main anthropogenic factor impacting surface soils' quality. Thus, it represented one of the best experimental sites to study PS impacts on tropical soils.

PS is well-known to be a source of organic matter, micronutrients (Fangueiro et al., 2010; Provolto and Martinez-Suller, 2007) but also high levels of Cu, Zn, Fe, Mn, Co and Cd (L'Herroux et al., 1997; Sánchez and González, 2005). In industrialized countries, many studies have shown the negative effects of intensive PS spreading for fertilization in modern agriculture practices leading to an increase of nitrogen, phosphorus and heavy metals such as Cu, Zn, Co, Mn in soil layers and/or ground water. These elements can remain in the soil or migrate by percolation or water run off inducing soil and water resources pollution (L'Herroux et al., 1997). Pig breeding in small Polynesian Islands is managed by households without PS management involving those piggeries effluents to be spread directly onto the soil. Family piggeries are mostly located on the coastal area which is particularly sensitive to inputs from the surface. On the coastal area, the groundwater is, indeed, showing on the soil surface. Even though family pig breeding is smaller in size as compared to industrial breeding, the absence of PS recovery induces a major risk of soil and water pollution. Moreover, volcanogenic tropical soils have naturally high metal contents (Doelsch et al., 2010). Thus PS inputs may affect soil physico-chemical parameters (pH, Eh, organic matter content, salinity ...) and consequently may affect metals speciation and mobility (Acosta et al., 2011; Gunkel et al., 2002). The risk of drainage of soluble species, inorganic nitrogen and soluble phosphorus, essential or detrimental metals provided by PS has to be evaluated. The influence of raw PS on the mobility of endogenous metals, naturally present at high concentrations in tropical soils, has to be evaluated as well.

Recent scientific studies confirmed the impact of PS on tropical soils physico-chemical properties' (Doelsch et al., 2010; Legros et al., 2013) in the case of well managed pig wastes and PS applications. It is well known that the chemical composition of PS has a great variability depending on storage conditions, on farming practices, on diets and also on the type of operation (Hansen et al., 2007; Sánchez and González, 2005). To our knowledge, no data are available for family farming conducted without PS management practices on tropical soils.

The objectives of the present study were then:

- (1) to determine the chemical composition of the raw PS produced by family farms;
- (2) to evaluate nitrogen and phosphorus content in soils impacted by long term raw PS inputs;
- (3) to compare metals (Ca, Mg Na, K, Fe, Mn, Al, Cu, Zn, Cr, Ni, Cd and Pb) contents and mobility; and
- (4) to compare the two family pig breeding systems: pig enclosure in small concrete pens and in large land pens.

2. Materials and methods

2.1. Description of studied sites

Uvéa, located in the Pacific Ocean, is in the Territory of Wallis and Futuna Islands (Fig. 1). The mean annual temperature is 28.6 ± 0.6 °C and the mean annual rainfall is 2.87 ± 1.68 m/year over the period 1973 to 1995 (Alory and Delcroix, 1999). The climate is tropical, hot and humid all over the year. Except for July (lowest precipitations) and April (highest precipitations), there is quite constant high

temperature and high monthly precipitations all over the year. The field campaign was conducted from 16th to 23th May 2011 and we can expect our data to be overall representative for an entire year. The island has an area of 96 km² and the population density is about 111.8 ih/km². The coastal strip and the first level plateau cumulate nearly all the population. The unique water resource is a groundwater reservoir which is refilled by annual precipitations and leaching across permeable basalts (Price et al., 1991; Stearns, 1945). It is thus particularly sensitive to surface inputs, especially at the periphery of the island because of the small soil thickness and of the presence of permeable calcareous sand. Contaminants can then easily reach the water resource by percolation at the coastal areas.

Three volcanic units are described with few geochemical variations (Price et al., 1991). Tropical volcanite alteration, impulsed 0.5 Ma ago, results in classical pure ferralitic soils (Tercinier, 1971). However, along the coast, volcanogenic alterites are mixed with calcareous clasts. Then three sites were selected (Fig. 1) to be representative of the pedological diversity that prevails in Uvéa. At Vaillala, two impacted soils were sampled A₁ (13°13.221'S, 176°176.198 W) and A₂ (13°13.265'S, 176°12.003 W) as well as their respective controls. According to the soils texture diagram (USA Taxonomy 1976) soils A₁ (sand 68.4%, silt 28.4% and clay 3.2%) and A₂ (sand 60.9%, silt 35.2% and clay 3.9%) are classified as sandy loam soil. At Mont-Afala (13°15.941'S, 176°10.919 W) and at Lanutavake (13°19.517'S, 176°12.759'W) four impacted soils were sampled, B₁, B₂ and C₁, C₂ respectively and their controls. Soils B₁ and B₂ (sand 19%, silt 72.9% and clay 8.1%) are classified as silt loam soil and soils C₁ and C₂ (sand 5.1%, silt 85.4% and clay 9.5%) are classified as silt soil.

2.2. Description of farming practices

Pig diets are traditionally made up of banana leaves, coconut, cassava root (manioc), and food wastes. Nowadays, diets include commercial pellets in a ratio of 25 to almost 100% of the diet. Pig's diets having an influence on chemical composition on PS (Hansen et al., 2007), we selected farms with 30 to 70% of the diets supplied by pellets.

Two kinds of pig production systems are in use (Fig. 2) and in both cases PS is not collected in a pit.

- Pigs are enclosed in small concrete pens with a density of 0.5 to 1.2 pig/m². The concrete pens are daily cleaned with a jet of water. Wash waters with urine and feces run off onto the soil and accumulate along the concrete pen on a soil surface of around one meter wide. PS is here a mixture of pigs' excretions and water.
- Pigs are enclosed in large land pens (100 to 600 m²) and with a pig density of 0.02 to 0.06 pig/m². PS is here pigs' excretions (urine and feces) emitted directly on the land floor. After 3 years in use the land pen is displaced and the soil is used as an agricultural land to take advantage of the fertilizing effects of PS accumulation.

2.3. Sampling

2.3.1. PS sampling

Just after a daily washing, four samples were collected in the slurry band along the concrete pens. Samples were separated as liquid and solid phases by centrifugation and analyzed separately.

2.3.2. Soil sampling

Samples were collected at various depths: at the surface (0–5 cm), at 25 cm and at 65 cm. Five samples were retrieved at each of the 10 sampling plots (on a surface of about 0.5 m²) of the three sites leading to the collection of 150 samples. The five samples representative for one plot were pooled and mixed as a single sample to reduce the number of samples to 30. Pig breedings were surrounded by the tropical forest and the original forest remained

Fig. 1. Location of Uvéa Island and of the three studied sites.

the only area not influenced by PS since deforestation occurred mainly for infrastructures (roads, houses...), crops and breeding. Controls were non-impacted soils collected in the original forest near the breeding area. The subscript 1 (A_1 , B_1 , C_1) was for samples collected near concrete pens, soils have been daily impacted by PS inputs for more than 7 years. Sampling was performed in the middle of the discharge area, after removing the slurry in order to collect soil sample (Fig. 2). The subscript 2 (A_2 , B_2 , C_2) was for samples collected in land pens, soils have been impacted daily by PS inputs for at least one year but no more than three years. Sampling was performed in the dirtiest area which was a preferential area of pig excretion containing lots of pig feces (Fig. 2).

All samples were frozen before aircraft transport and analysis.

2.4. PS and soil chemical analysis

The dry matter of samples (soils and of PS solid phase) was determined by drying at 105 °C for 12–20 h until a constant weight was reached.

Electrical conductivity (EC) and pH were measured on PS liquid phase, on water extracts of soils or PS solid phase. 1/5 (w/w) extracts were prepared by mechanically shaking 20 g of solid sample in 100 mL of deionized water for 1 h, followed by 1 h of undisturbed settling before measurement. The Total Inorganic Nitrogen ($TIN = N-NO_3^- + N-NO_2^- + N-NH_4^+$) in water extracts was determined by colorimetry with a WTW Measurement System. The Total Kjeldahl Nitrogen (TKN) content was determined by the Kjeldahl method.

Fig. 2. Family pig farming systems: enclosure of pigs in small concrete pens or in a large land pens.

PS and soil samples were analyzed for Total Phosphorus (TP) and total metal content (Ca, Mg, Sr, Na, K, Fe, Mn, Al, Cu, Zn, Ni, Cr, Pb and Cd) after alkaline digestion ($\text{Li}_2\text{B}_4\text{O}_7/\text{LiBO}_3$ at 1100 °C (NF ISO 14869–2)).

TKN and TP contents in PS liquid phase couldn't be determined because of the small amount of the liquid phase.

A selective extraction procedure using ammonium nitrate solution (1 mol/L for a ratio of 1/2.5 (m/V) according to the standard procedure ISO/DIS19730 (2006)) was performed on soil samples collected at 0–5 cm depth in order to access the exchangeable fraction of P, Ca, Mg, Sr, Na, K, Fe, Mn, Al, Cu, Zn, Ni, Cr, Pb and Cd.

Metals quantification was carried out by ICP-OES (Optima 3300 VD, PerkinElmer). Quality control included triplicate analyses and analytical Standard Deviation (RSD) was below 7%. Metal concentrations in blanks were below the detection limit.

2.5. Contamination Factor (CF) and Pollution Load Index (PLI)

Contamination Factor and Pollution Load Index were both used in this study to examine the contamination of soils. They have been widely used to assess heavy metals contamination in various environments (Gwod et al., 2010; Iqbal and Shah, 2011; Li et al., 2014). Many studies used the average values of shale or crustal abundance as a reference baseline. Since no data on background concentrations for Uvêa Island were available, the alternative was to compare concentrations between contaminated soils and controls.

- CF was calculated for each soil according to Eq. (1) :

$$CF = \frac{[X]_{\text{impacted}}}{[X]_{\text{control}}} \quad (1)$$

with $[X]_{\text{impacted}}$ the concentration of the element X in a soil impacted by PS and $[X]_{\text{control}}$ the concentration of X with the same unit in the soil control at the same depth. CF was calculated for total concentrations (Table 3) and for exchangeable concentrations (Table 5) in order to get the influence of PS on metal mobilization. CF were classified as nil or low when $CF \leq 1.0$, as moderate when $1.0 < CF \leq 3.0$, as considerable when $3.0 < CF \leq 6.0$ and as very high when $CF > 6$ (Fujita et al., 2014; Håkanson, 1980).

- The PLI was the nth root of the product of the CF determined for the n studied metals (here Fe, Mn, Al, Cu, Zn, Cr and Ni: $n = 7$) according to Eq. (2):

$$PLI = \left(\prod_{i=1}^n CF_i \right)^{1/n} \quad (2)$$

$PLI > 1$ indicates that heavy metal pollution exists (Tomlinson et al., 1980).

3. Results and discussion

3.1. Chemical composition of raw PS (Table 1)

The pH of raw PS recorded in Uvea ranged from 6.7 to 7.6, according to values found in the literature (6.7 to 9.8) (De la Torre et al., 2000; Moral et al., 2005; Payet et al., 2009; Provololo and Martinez-Suller, 2007; Van der Stelt et al., 2005).

EC of liquid and solid phase ranged from 1.5 to 2.3 dS.m⁻¹. Digested PS collected in tanks have higher EC (1.5 to 75.2 dS.m⁻¹) (De La Torre et al., 2000; Moral et al., 2005; Provololo and Martinez-Suller, 2007; Sánchez and González, 2005) indicating that the soluble ions content was lower than in digested PS.

The solid phase contained high contents of TKN and TP (3.1 to 14.2 g.kg⁻¹) in agreement with the literature (Legros et al., 2013; Sánchez and González, 2005). TIN content was low in liquid and solid phases (0.4 to 12.0 mg.L⁻¹ and 0.003 to 0.011 g.kg⁻¹ respectively) because around one thousand less concentrated than for industrial digested PS (0.4 to 10.8 g/kg, Sánchez and González (2005); 2.8 g/kg, Fanguero et al. (2010)). These findings are in agreement with EC results.

The liquid phase was a significant source of K, Na, Ca, Mg, Fe, Al, Mn and Sr classified by order of importance (0.1 to 26 mg.L⁻¹). Cu, Zn, Cr and Ni were trace elements (0 to 30 µg.L⁻¹). Nor Pb nor Cd was detected. The liquid phase was thus not a supply of high quantities of Cu, Zn, Cr and Ni. The solid phase contained very high concentrations of Ca, Mg, Sr, Na, K, Fe, Mn and Al (up to 0.3 g.kg⁻¹) and Zn, Cu, Cr and Ni (up to 20 mg.kg⁻¹). The solid phase was thus a supply of high quantities of metals including Zn, Cu Cr and Ni.

Compared to digested PS, the outdoor raw PS had 10 to 100 times higher Cr contents (Doelsch et al., 2010), 100 times higher Fe and Al contents (Sanchez et al., 2005; Legros et al., 2013), similar Ca, Mg and Ni concentrations (Doelsch et al., 2010; Legros et al., 2013; Sánchez and González, 2005), had 10 times smaller to similar Na and K concentrations and had 5 times lower to similar Cu and Zn contents (Doelsch et al., 2010; Legros et al., 2013; Li et al., 2010).

As a conclusion, the outdoor raw PS was here characterized by a low electrical conductivity with low inorganic nitrogen content. The liquid and solid phases were a high source of Ca, Mg, Sr, Na, K, Fe, Mn and Al while the solid phase was also an important source of Cu, Zn, Cr and Ni. PS was here particularly rich in Fe, Al and Cr.

3.2. Description of soils controls (Table 2)

TKN content in controls ranged from 0.3 to 7.5 g/kg and decreased with depth that was consistent with the nitrogen supply by the important layer of dead leaves covering the soil. TKN (sum of ammonium and organic nitrogen) was here mainly organic nitrogen since TIN (nitrates, nitrites and ammonium) was lower than 2.1 mg-N/kg that represented less than 3% of TKN.

Table 1
Minimum (min) and maximum (max) values for parameters measured in the liquid and solid phase of raw pig slurry samples ($n = 4$) and the Relative Standard Deviation RSD (%). na: not analyzed.

	pH	EC	TKN	TIN	TP	Ca	Mg	Sr	Na	K	Fe	Mn	Al	Cu	Zn	Cr	Ni	Pb	Cd
Liquid phase		dS.m ⁻¹	mg.L ⁻¹			mg.L ⁻¹								µg.L ⁻¹					
Max	7.6	2.3	na	12.0	na	4.6	4.1	0.8	5.7	26.0	2.9	0.9	1.4	5	2	30	4	<1	<1
Min	6.7	1.5	na	0.4	na	1.0	1.9	0.2	1.2	9.9	1.5	0.1	0.1	1	<1	20	1	<1	<1
RSD	6	21	–	132	–	55	29	68	62	45	10	141	150	53	–	16	41	–	–
Solid			g.kg ⁻¹			g.kg ⁻¹								mg.kg ⁻¹					
Max	7.2	1.4	14.2	0.011	15.1	46.16	7.1	0.7	2.5	10.6	183.1	6.3	151.7	170	400	909	140	1	2
Min	7.1	0.7	5.3	0.003	3.1	5.9	2.9	0.4	0.5	0.6	12.4	0.5	9.3	70	210	90	20	<0.5	<0.5
RSD	1	47	51	73	65	71	41	37	83	141	98	94	98	40	31	95	74	–	–

Table 2

Physicochemical properties of soils controls sampled at various depths: 0 cm, 25 cm and 65 cm.

Controls		pH	EC	TKN	TP	TIN	Ca	Mg	Sr	Na	K	Fe	Mn	Al	Cu	Zn	Cr	Ni
Sites	cm		dS.m ⁻¹	g.kg ⁻¹		mg-N/kg	g.kg ⁻¹	g.kg ⁻¹							mg.kg ⁻¹			
A ₁	0	7.7	0.2	5.2	2.4	1.9	295.2	1.5	5.3	2.0	0.3	20.2	0.7	15.8	29	75	133	23
	25	8.1	0.1	0.7	0.5	2.1	381.2	0.5	7.5	2.1	0.05	5.2	0.1	3.4	4	<0.5	36	1
	65	8.4	0.6	1.0	0.6	0.4	390.1	1.2	7.1	2.1	0.06	5.8	0.2	3.8	10	<0.5	48	3
A ₂	0	7.6	0.4	7.5	2.2	0.003	284.3	0.9	5.3	1.5	0.3	15.7	0.5	11.9	15	20	88	15
	25	7.3	0.2	4.9	1.7	0.002	304.1	0.8	5.7	1.7	0.2	17.3	0.5	12.7	13	13	125	20
	65	8.6	0.3	0.6	0.4	0.0004	439.8	2.7	5.6	1.9	0.1	5.8	0.2	3.7	3	25	54	8
B ₁ /B ₂	0	5.7	0.1	3.2	0.9	1.3	1.1	2.8	0.03	0.6	0.2	185.7	4.6	150.9	148	370	1020	167
	25	5.6	0.1	1.0	0.7	1.3	0.1	2.4	0.01	0.1	0.01	218.4	3.5	171.3	164	148	1136	145
	65	5.4	0.2	0.3	0.6	0.9	0.1	2.4	<0.01	0.1	0.01	218.6	4.2	173.3	169	142	1091	143
C ₁ /C ₂	0	6.0	0.9	3.7	1.6	1.4	6.3	7.6	0.08	1.6	1.0	194.1	4.2	105.0	115	274	1368	517
	25	5.9	0.2	2.1	1.2	0.8	3.7	6.6	0.05	1.5	0.8	187.2	3.4	119.1	118	262	1206	556
	65	5.8	0.5	0.7	1.1	0.6	2.2	5.0	0.08	1.1	0.3	166.4	2.0	132.1	104	176	867	565

At Vaillala, in the coastal area (Fig. 1), controls for A₁ and A₂, were characterized by alkaline pH values, very high Ca contents (295.2 to 439.8 g/kg) and high Fe, Al, Sr and Mg contents (0.5 to 20.2 g/kg). They were characteristic of mixed calcareous soils.

At Mont-Afala and at Lanutavake, inland (Fig. 1), controls for B₁ and B₂ and for C₁ and C₂ were slightly acidic and characterized by very high Fe and Al contents (105.9 to 218.6 g/kg) and high Mn and Mg contents (2.0 to 7.6 g/kg). Their Cu, Zn, Ni, Cr, Pb and Cd contents were much more important than for coastal soils. They were characteristic of pure ferralitic soils with quite similar composition, differing slightly by their Ca, Sr, Na, K and Ni contents.

3.3. Nitrogen and phosphorus contamination of soils

Despite the large amount of TKN in PS (Table 1), only 3 samples exhibited a considerable or a very high CF for TKN (Table 3). The small TKN accumulation in most samples, after nitrogen supply by PS, could be attributed to a loss of N-ammonia by volatilization, N uptake by crops and/or nitrification (Jones et al., 2007; Morvan et al., 1997; Paul and Beauchamp, 1994).

For TIN, very high or considerable CF values were noticed in most samples (Table 3). TIN content in PS solid phase was low in comparison with the literature (3–11 mg-N/kg) (Table 1) but it was anyway ten

times more concentrated than in soils controls (Table 2). Raw PS remained then an important source of TIN. Samples collected near concrete pens (A₁, B₁ and C₁) had higher CF values than those collected in land pens. PS accumulation near concrete pens was thus an important source of inorganic nitrogen. The high TIN contamination was also here due to in situ organic nitrogen mineralization of PS and by ammonium nitrification (Müller et al., 2003; Roth et al., 2014) in accordance with the low TKN CF.

For TP, very high or considerable CF values were noticed for four samples but in most cases CF was moderate or low (Table 3). Pig breeding on concrete pens (A₁, B₁ and C₁) induced usually higher CF for TKN, TIN and TP than breeding in land pens (A₂, B₂ and C₂) (Table 3).

The exchangeable P content (Table 4) which was mainly phosphate ions was low in controls (below 1.4 mg.kg⁻¹) and it increased only for calcareous soils (190 and 42 mg.kg⁻¹ mg/kg for A₁ and A₂ respectively) in agreement with concentrations measured by Plaza et al. (2004). In impacted pure ferralitic soils, the exchangeable P content was not detected indicating that even though these soils were enriched with phosphorus, it was not exchangeable. This was due to phosphate adsorption on Fe and Al hydroxides and oxyhydroxides (Daroub et al., 2003; Fontes and Weed, 1996; Yerokun, 2008). Phosphate ions can't be drained to the groundwater in pure ferralitic soils but they can easily be in mixed calcareous soils.

Table 3

Contamination Factors (CFs) for soils impacted by PS and Pollution Load Index (PLI) calculated for Fe, Mn, Al, Cu, Zn, Cr and Ni. na: not analyzed. Light blue colored boxes for moderate contamination, medium blue ones for considerable contamination and dark blue ones for very high contamination.

Soils	Sites	depth	TKN	TIN	TP	Ca	Mg	Sr	Na	K	Fe	Mn	Al	Cu	Zn	Cr	Ni	PLI
Mixed calcareous	A ₁	0	2.5	1.8	4.2		3.0			6.4				2.8	5.2		1.8	1.3
		25	5.0	6.2	11.4		4.0			12.2	2.6	2.7	3.1	8.9	9.2	3.3	27.1	5.5
		65		23.8	1.6		2.0			3.8								0.5
	A ₂	0		2.2	2.1		2.0			1.3	1.2		1.2	1.8	25.2	1.5	6.1	2.5
		25			1.2		1.1			1.3				1.1	20.4			1.0
		65	7.5	14.3	4.2					3.2	2.1	1.1	2.9	4.9	3.5	1.6	1.7	2.3
Pure ferralitic	B ₁	0	1.7	3.4	1.8	5.2		2.8		3.6		1.2		1.1				0.9
		25		5.7		2.5		6.7	1.4	11.7		1.7		1.1				1.0
		65	1.5	9.0		3.0		12.2	1.4	11.6		1.5						1.0
	B ₂	0	na	2.2	na	na	na	na	na	na	na	na	na	na	na	na	na	na
		25				1.1			1.6	3.2		1.6		1.1			1.1	1.1
		65		5.5	1.2		1.1		3.0	8.7		1.9		1.3	1.2	1.1	1.4	1.3
Pure ferralitic	C ₁	0	4.7	4.1	8.8	5.9	1.2	4.1		4.5					2.1			0.7
		25		11.7	1.3	1.2		1.3		1.6								0.9
		65		11.7	1.2	1.3	1.3		1.1	3.4		1.2		1.1			1.2	1.0
	C ₂	0			1.4					2.7								0.9
		25	1.6		1.6	1.5	1.2	1.3	1.2	3.2								1.0
		65			1.4	1.1	2.0			2.6		1.2		1.2			1.1	1.1

Table 4
Exchangeable contents in mg.kg⁻¹ in soils sampled at the surface (0 cm depth).

	Sites	P	Ca	Mg	Sr	Na	K	Fe	Mn	Al	Cu	Zn	Cr	Ni
Controls	A ₁	1.4	2950	101	63	22	96	2.1	0.5	1.7	0.2	0.60	<0.01	<0.01
	A ₂	1.2	3400	73	97	15	99	4.4	1.0	4.1	0.2	0.02	<0.01	<0.01
	B ₁ /B ₂	<0.1	580	150	11	41	76	14.5	141.1	13.7	0.1	1.02	0.01	0.43
	C ₁ /C ₂	<0.1	3055	1047	38	187	199	20.7	47.2	16.8	0.2	0.40	0.02	0.20
Impacted soils	A ₁	190	4095	710	81	85	795	13	3.1	8.8	0.8	1.10	0.07	0.04
	A ₂	42	3720	360	90	57	645	16	1.3	14.0	0.5	1.20	0.06	0.04
	B ₁	<0.1	3795	243	70	55	260	13	2.1	10.1	0.5	0.06	<0.01	<0.01
	B ₂	<0.1	1565	545	25	140	750	10	89.5	8.2	0.2	0.84	<0.01	0.04
	C ₁	<0.1	4560	930	45	53	844	8	9.4	6.3	0.2	2.10	<0.01	0.05
	C ₂	<0.1	3055	1050	32	45	790	8	20.8	6.3	0.2	0.50	<0.01	0.08

3.4. Increase of soils salinity

Soils impacted by PS exhibited higher EC than their control (the ratio at the surface EC_{impacted}/EC_{control} was 6.5 and 8.6 for A₁ and A₂ respectively, 5.5 for B₁, 3.3 and 2.7 for C₁ and C₂ respectively).

Ca, Mg, Sr, Na and K were highly concentrated in PS liquid and solid phases (0.2 to 26.0 mg.L⁻¹ and 0.4 to 41.6 g.kg⁻¹ respectively) (Table 1). Even though, CF values for total Ca, Mg, Sr and Na were not systematically high because their concentrations in PS was, depending on the soils considered, irrelevant in front of natural total contents. CF values for total K indicated that at least a moderate contamination existed (Table 3). K was accumulated in all cases and a significant positive correlation (R² = 0.762) was obtained between EC and total K content in all soils samples (controls and impacted ones) indicating that EC increase was mainly related to K enrichment. CF values for the exchangeable fraction of K were always considerable or very high (Table 5). CF for the exchangeable fraction of Ca, Mg, Sr and Na were above one (except Sr at A₂, Mg and Na for C₁ and except for C₂) indicating that these elements contributed to increase soils EC. Beside inorganic nitrogen enrichment in impacted soils, the soil salinity increase was related to Ca, Sr, Mg, Na and K supply.

These metals have no detrimental effects but it is known that salinity increases the mobility of heavy metals in soils or sediments by competition for sorption sites (Acosta et al., 2011; Zhao et al., 2013). Salinization due to PS inputs has thus to be taken into account when assessing the risk on heavy metals release.

3.5. Heavy metals contamination in calcareous soils

Fe, Mn and Al were highly concentrated in PS liquid and solid phases (0.1 to 2.9 mg.L⁻¹ and 0.5 to 183.1 g.kg⁻¹ respectively) (Table 1). Consequently for calcareous soils (A₁ and A₂) naturally poor in Fe, Al and Mn (Table 2), CF values indicated moderate to high contaminations, at least at one layer (Table 3). Calcareous soils were naturally poor in Cu, Zn, Cr and Ni (Table 2) thus PS inputs (20 to 909 mg.kg⁻¹ in PS solid phase) (Table 1) induced also moderate to high CF for total contents at least at one depth (Table 3). The PLI index (Table 3) demonstrated

that heavy metals pollution existed (1.3, 5.5 for A₁ at 0 and 25 cm depths and 2.5 and 2.3 for A₂ at 0 and 65 cm depths).

Additionally, CF values for the exchangeable fraction of Fe, Mn, Al, Cu and Zn indicated that PS inputs induced moderate to very high contamination in this soil fraction (Table 5). It demonstrates that either PS provided exogenous soluble Fe, Mn, Al, Cu and Zn or endogenous Fe, Mn, Al, Cu and Zn became exchangeable. CF for the exchangeable fraction of Cr and Ni could not be calculated; they were detected in impacted soils (Table 4) but not in controls indicating that they were mobile in impacted soils. With PS inputs, soil pH decreased (0.5 and 0.1 unit for A₁ and A₂ respectively at the surface) and soil salinity increased. Both parameters are known to have a positive influence on metals's solubility and thus metals' mobility (Gunkel et al., 2002; Zeng et al., 2011). In impacted mixed calcareous soils Fe, Mn, Al, Cu, Zn, Cr and Ni mobility enhancement was related to pH decrease and salinity increase.

3.6. Heavy metals contamination in ferralitic soils

Fe and Al contents were naturally high in ferralitic soils (B₁, B₂, C₁ and C₂) (Table 2). CF for total Fe and Al always indicated a nil contamination (Table 3) because Fe and Al supply by PS was insignificant in front of natural high contents. Mn supply could be detected in front of natural contents (Table 2) inducing a moderate contamination at least at one depth (Table 3). Few CF values indicated moderate Zn, Cr and Ni contaminations (Table 3) because they were minor elements in PS. Among minor elements in PS, Cu was the one with lowest concentrations in ferralitic soils (Table 2) thus Cu supply was relevant and its CF indicated moderate contamination at least at one depth (Table 3). Some PLIs for breeding in land pens were slightly up to one (Table 3) demonstrating a small heavy metals pollution (1.1, 1.3 for B₂ at 25 and 65 cm depth and 1.1 for C₂ at 65 cm depth).

CF for the exchangeable fraction of Fe, Mn and Al were below 1 (Table 5) underlying that the exchangeable content of Fe, Mn and Al decreased with PS inputs. For Cr and Ni, CF could not be calculated because they were not detected in most impacted soils (Table 4) while they were in controls (Table 4) indicating that their concentrations decreased in the exchangeable fraction. With PS, the soil pH has increased of 1.4, 0.7, 1.4 and 1.4 pH units for B₁, B₂, C₁ and C₂ respectively. Yuan et al. (2007) demonstrated that Cu and Cd desorption in soils increases with the increase of ionic strength while the desorption decreases with the rise of pH. They explained that desorption mechanism is a competition of complexation, adsorption and precipitation. For Fe, Mn, Al, Cr and Ni, the net effect of all these competitive reactions was here a decrease of their mobility. Results for Zn were variable. For B₁ and B₂, CF values were below one indicating here its immobilization like Fe, Mn, Al, Cr and Ni. Zn and Mn immobilization in contaminated soils had also been observed after "alperujo" compost application (Alburquerque et al., 2011). But a considerable contamination is noticed for Zn in C₁ (Table 5) and for Cu in B₁, B₂ and C₁. Humic and fulvic acids in PS are characterized by a very small Cu(II) and Zn(II) binding capacity and stability constant with respect to natural soil humic and fulvic acids

Table 5
Contamination Factors in the exchangeable fraction for soils impacted by PS. Light blue colored boxes for moderate contamination, medium blue ones for considerable contamination and dark blue ones for very high contamination.

Depth: 0 cm		Ca	Mg	Sr	Na	K	Fe	Mn	Al	Cu	Zn
Mixed calcareous	A ₁	1.4	7.0	1.3	3.9	8.3	5.8	6.7	5.3	4.0	1.8
	A ₂	1.1	4.9	0.9	3.8	6.7	3.5	1.3	3.5	2.5	54.9
Pure ferralitic	B ₁	6.6	1.7	6.1	1.4	3.4	0.9	0.02	0.8	5.0	0.1
	B ₂	2.7	3.6	2.2	3.4	9.9	0.7	0.7	0.6	2.0	0.8
Pure ferralitic	C ₁	1.5	0.9	1.2	1.0	4.2	0.4	0.2	0.4	1.5	5.3
	C ₂	1.0	1.0	0.9	0.9	4.0	0.4	0.4	0.4	1.0	1.0

(Hernández et al., 2006; Plaza et al., 2005). Cu and Zn could anyway move in the exchangeable fraction by binding with soluble organic matter provided by PS. Dissolved organic matter chelating properties are known to be improved by an increase of pH due to deprotonation of binding functions. High CF in the exchangeable fraction for Cu was then probably due to its chelation with dissolved organic matter. Zn is known to be less mobilized than Cu with organic acids (Pérez-Esteban et al., 2013). B₁ and B₂ had lower pH than C₁ at the surface (7.1, 6.4 and 7.4 respectively) and dissolved organic matter binding capacity enhancement and the EC enhancement could probably not counterbalance Zn immobilization by soil alkalisation. The exchangeable Cu, Zn, Cr and Ni content remained anyway low in comparison with previous metals (below 2.1 mg.kg⁻¹) (Table 4) in agreement with values measured in tropical ferralitic soils in Reunion Island amended by PS (Doelsch et al., 2010).

4. Conclusion

To the best of our knowledge, this study is the first of its kind on family pig farming in tropical islands. A long term application of raw pig slurry on soils can lead to an increase of nitrogen, phosphorus and metals contents. The soil layer that concentrates inputs is not necessary the top layer, it is thus important to collect soils samples at various depths.

This study underlines that the behavior of contaminants is related to the nature of the tropical soil. For mixed calcareous soils at the coastal area, a fraction of phosphorus is mobile and soils are enriched with Fe, Mn, Al, Cu, Zn, Cr and Ni which are exchangeable. Pig breeding may then induce fluxes of these elements to the ground water. For inland pure ferralitic soils, P, Fe, Mn, Al, Cr and Ni are immobilized. Cu remain mobile and sometimes Zn as well. Inland, several meters of soils separate the soil surface from the groundwater limiting the drainage risk of contaminants. Detrimental effects of pig slurry can be important for mixed calcareous soils at the coastal area concentrating moreover most inhabitants.

Globally, pig breeding on concrete pens induces higher Contamination Factors for organic nitrogen, inorganic nitrogen and total phosphorus than breeding in land pens.

Based upon these results and for groundwater preservation, it is then recommended to limit family pig breeding on concrete pens without pig slurry management on coastal calcareous soils and rather encourage the use of large land pens on ferralitic soils in Uvéa and by spread in volcanic islands in the south Pacific.

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