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Effect of plant species on sludge dewatering and fate of pollutants in sludge treatment wetlands

Vincent Gagnon[a], Florent Chazarenc[b], Yves Comeau[c], Jacques Brisson[a,*]

[a] Institut de Recherche en Biologie Végétale, Département de Sciences Biologiques, Université de Montréal, 4101 Sherbrooke Est, Montréal, Québec, H1X 2B2 Canada

[b] L'UNAM Université, École des Mines de Nantes, CNRS, GEPEA, UMR 6144, 4 rue Alfred Kastler, B.P. 20722, F-44307 Nantes Cedex 3, France

[c] Department of Civil, Geological and Mining Engineering, École Polytechnique, Montréal, Québec, H3C 3A7 Canada

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ABSTRACT

Plants are assumed to play a central role in sludge treatment wetlands (STWs) by preventing clogging, favouring dewatering and improving sludge mineralisation. However, few comparative studies have been made to assess the influence of plants presence or species on the treatment of sludge in STWs. Therefore, the aim of this study was to evaluate the effect of three plant species on sludge dewatering and mineralisation, and on the general fate of water and pollutants in STWs. The experimental setup consisted of mesocosm sized STWs planted with monocultures of *Phragmites australis*, *Typha angustifolia* and *Scirpus fluviatilis*, in addition to an unplanted control, each in duplicate. The mesocosms were fed with settled fish farm sludge for three summers, and the effect of plants was assessed according to the percentage of pollutants per mass of dry sludge (pollutant content), in addition to a mass balance analysis of pollutants in the STWs.

Results revealed that the standard method for assessing STW efficiency (i.e. sludge pollutants content) is inadequate when comparing the subtle effect of plant species and that a mass balance analysis should be used instead. Mass balance showed that pollutants were mainly retained within the sludge cake, while the rest was considered trapped inside the STWs or mineralised. Only a small percentage of pollutants was discharged at the effluent (from <0.1% to 5% of total pollutants input). Plant species had a distinct effect on pollutants, which differed according to the sampling location in the STWs. At the outlet, pollutant removal was more efficient in the planted system and was significantly different according to plant species. In the sludge cake, contrary to common assumptions, STWs planted with *T. angustifolia* and *S. fluviatilis* had generally higher sludge cake volume, mass of organic matter, nitrogen and phosphorus, when compared to the unplanted control. This was attributed to the presence of plant litter in the sludge cake, which mitigated mineralisation. In contrast, STWs planted with *P. australis* resulted in the highest reduction in sludge volume and were the most efficient for sludge dewatering and mineralisation of organic matter in comparison to other species and the unplanted control. A fraction of the nitrogen and phosphorus was also sequestered in plant tissues, which represented close to a quarter of the nitrogen input by the sludge in *P. australis* STWs. This study shows that the presence of plants and the choice of plant species is an important factor that affects sludge dewatering and mineralisation, but also the general fate of water and pollutants in STWs. Further studies should be done in a full size STW to validate the finding obtained in this mesocosm experiment.

1. Introduction

Sludge treatment wetland (STW) is a phytotechnology specialised in the reduction of sludge volume, by the means of dewatering and mineralisation process. Plants are thought to play a central role in STWs, by preventing clogging, favouring dewatering and improving mineralisation of the sludge (Nielsen, 2007). They are assumed to enhance dewatering through plant transpiration and by creating drainage tunnels within the sludge layer through the movement of stems and roots (Nielsen, 2003). Furthermore, aeration from the tunnels as well as oxygen transfer from the plant to the rhizosphere are considered to favour microbial processes responsible for the mineralisation of the sludge cake (Uggetti et al., 2010).

* Corresponding author. Tel.: +1 514 343 2116; fax: +1 514 343 2288.
E-mail address: jacques.brisson@umontreal.ca (J. Brisson).

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Although plants constitute a key element of this technology, few studies have tested the influence of plants or plant species on the dewatering and mineralisation of the sludge. Essentially all studies comparing planted to unplanted STWs were conducted using *Phragmites australis*, sometimes with contradictory findings. The presence of *P. australis* has been shown to enhance sludge volume reduction, with 3–8% less volume in planted systems compared to unplanted controls (Edwards et al., 2001; Stefanakis and Tsihrintzis, 2012). *P. australis* can similarly favour dewatering, with an average of 2–6% more total solids content (TS) in the sludge cake compared to unplanted control (Edwards et al., 2001; Stefanakis and Tsihrintzis, 2012). However, a study by Liénard et al. (1995) measured no TS difference between the sludge cake of planted and unplanted STWs. Sludge mineralisation was higher in planted systems, with 3–6% less total volatile solids content (TVS) per TS in the sludge cake (Liénard et al., 1995; Stefanakis and Tsihrintzis, 2012), yet one study measured no difference (Edwards et al., 2001). A lower percentage of nutrients has generally been found in the sludge cake of planted STWs, with 1–6% less total Kjeldahl nitrogen content (TKN) and 0.3–3.5% less total phosphorus content (TP) per TS (Liénard et al., 1995; Stefanakis and Tsihrintzis, 2012). Little attention has been given to the effect of plant species in STWs. To date, the single study comparing the effect of plant species on the dewatering and mineralisation of sludge revealed no significant difference between *P. australis* and *Typha* sp. in terms of volume reduction, chemical oxygen demand (COD), TS, TVS, TKN and TP removal (Uggetti et al., 2012). However, the significance of any effect of plant presence or particular species in STWs is difficult to assess, since these experiments were conducted without replicated units. Variance for each treatment is therefore unknown or, if presented (spatial or temporal sub-sampling of the same STW units), it is usually too large to allow a clear interpretation.

The pollutant content of sludge gives only the ratio of pollutants per solids, but not the specific mass of pollutants accumulated within the sludge cake of the STW. This can be a significant bias when comparing subtle differences between treatments, since at the same ratio (e.g. 30% TVS/TS) planted STWs could have a proportionally lower mass of TVS and TS per surface than the unplanted STW, but still result in the same pollutant content. Therefore, the effect of plants in STWs could be better assessed using a mass balance analysis, which gives the amount of water and pollutants retained in the sludge cake, sequestered in the plant, transformed or discharged at the outlet. Water balance analysis of STWs planted with *P. australis* has shown that a large proportion is eliminated through evapotranspiration (58–84%), most of the rest being discharged at the outlet (13–41%), and only a small fraction being retained in the sludge cake (1–4%) (Begg et al., 2001; Stefanakis and Tsihrintzis, 2011). Water balance analysis of STWs planted with *Typha angustifolia* found a lower percentage of water loss through evapotranspiration (42%), with the remaining water considered discharged at the outlet (58%) (Panuvatvanich et al., 2009). In STWs planted with *T. angustifolia*, total solids were retained mainly in the sludge cake (38–52%), with only 11–12% present at the outlet and the rest unaccounted for (36–50%) (Koottatep et al., 2001). Another study found that nitrogen was mainly retained in the sludge cake (55%), a very small portion was sequestered in *T. angustifolia* tissues (0.2%), and the rest was discharged at the outlet (13%) or unaccounted for (13%) (Panuvatvanich et al., 2009). None of these studies reported a comparative analysis of mass balance between plant species under similar experimental conditions. Consequently, the effect of plants species on the fate of water and pollutants in STWs remains inconclusive.

The aim of this work was to evaluate the effect of the presence of plants and specific plant species on sludge dewatering and mineralisation, and to determine the fate of water and pollutants in sludge treatment wetlands. The experiment was conducted over three summers in mesocosm sized STWs planted in monoculture of *P. australis*, *T. angustifolia* and *S. fluviatilis*, and compared to an unplanted control, all in duplicates. The experimental STWs were not completely drained, and a saturated layer was retained at the bottom of the wetland to favour evapotranspiration and pollutants removal. The experimental systems were fed with concentrated fish farm sludge, and the performance was evaluated by the efficiency of sludge dewatering and mineralisation, as well as by mass balance analysis.

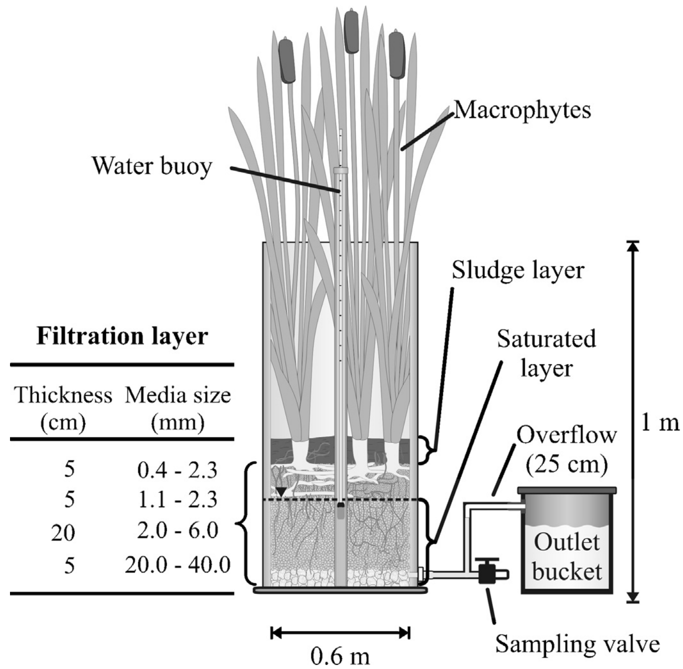

Fig. 1. Cross section of the mesocosm showing the granular size of each filtration layer.

2. Materials and methods

2.1. Experimental design

The experiment was conducted in a field located at the Montreal Botanical Garden (Quebec, Canada), which has a semi-continental climate with warm, humid summers and very cold winters. The mean monthly temperature reaches a maximum of 20.9 °C in July and a minimum of −10.2 °C in January. Average annual precipitation is 979 mm (22% as snow), and the growing season lasts for about 195 days, from mid-April to mid-September (Environment Canada, Climate Normals 1971–2000). The experimental setup consisted of mesocosm-sized sludge treatment wetlands (cylindrical shape; height: 1 m; diameter: 0.6 m), each composed of 4 filter layers of different granular sizes (see Fig. 1 for details). Contrary to conventional STWs, the experimental mesocosms were not completely drained, and a saturated layer was retained by placing an overflow at 25 cm from the bottom. All water coming out from the overflow was recovered in an outlet bucket for sampling. Each mesocosm was planted with a monoculture of *P. australis*, *T. angustifolia*, *S. fluviatilis* and a fourth remained an unplanted control. All STWs treatment were in duplicate for a total of 8 mesocosms. A randomized block design was used for distributing the plant species among the mesocosms.

Table 1
Average of pollutant concentrations in the fresh sludge and total loading of pollutants per surface of STW after the third summer of feeding.

Pollutants in sludge	Concentration ($g L^{-1}$)	Total pollutants input ($kg m^{-2}$)
Total solids (TS)	32.5 ± 14.0	17.4
Total volatile solids (TVS)	23.5 ± 13.0	12.4
Total Kjeldahl nitrogen (TKN)	2.0 ± 0.8	0.91
Total phosphorus (TP)	0.75 ± 0.2	0.42

2.2. Pollutant characteristics and loading rates

The mesocosms were fed with fish farm sludge, which is mainly composed of settled fish faeces and uneaten food (Naylor et al., 1999) and is comparable to septage sludge in terms of pollutants composition and concentration (Troesch et al., 2009; Vincent et al., 2011). Average characteristics of the sludge and total input of pollutants are shown in Table 1. The mesocosms were planted at the end of the summer of 2007 and initially supplemented with 1500 g TS m^{-2}, followed by a weekly loading of fish farm sludge during the summers of 2008, 2009 and 2010. Loading was intermittent (1 day of feeding followed by 6 days of rest) with a weekly rate of 412 g TS m^{-2} wk^{-1} for 2008 (9 wk), 338 g TS m^{-2} wk^{-1} for 2009 (12 wk) and 575 g TS m^{-2} wk^{-1} for 2010 (14 wk) for a total of 0.59 m^3 m^{-2} of fish farm sludge during the experiment. The loading rate of this study (30 kg TS m^{-2} yr^{-1} in 2010) was lower than the common loading rate of 50–60 kg TS m^{-2} yr^{-1} for septic sludge in STWs (Nielsen, 2003; Troesch et al., 2009; Vincent et al., 2011), since fish farm sludge contains a high level of ammonia (NH_4-N: 500 mg N L^{-1}), which can be lethal to plants (Clarke and Baldwin, 2002). The mesocosms were not fed during winter, since the aim of this study was to measure the influence of plant species, which is expected to be minimal in STWs at freezing temperatures.

2.3. Sampling

Samples were taken from three locations: (1) the sludge cake at the surface of the STW, (2) the saturated layer of the STW and (3) the system outlet (Fig. 1). Core samples of the sludge cake were collected 1 week after the last sludge application with a plastic cylinder (1.4 cm in diameter) at two random points within the wetland and sludge height was recorded. Part of the core sludge sample was analysed immediately for TS and TVS, while the rest was dried and stored at 4 °C for subsequent analysis of TKN, TP and total carbon (TC). The saturated layer of the STWs was sampled at the end of the experiment by opening a valve located at the base of each mesocosm to collect a volume of 300 mL. Water volume in the saturated layer was also estimated by using a calibrated water buoy installed in each STW; the volume was then used to calculate the mass of pollutants in the saturated layer at the end of the experiment. The outlet bucket was checked daily for the presence of water, and if present, the volume was measured and the water transferred to a container stored at −20 °C. At the end of each week, the container was thawed and mixed, then analysed for TS and TVS. A subsample of the outlet water was refrozen (−20 °C) and subsequently analysed for total phosphorus (TP), total Kjeldahl nitrogen (TKN) and total carbon (TC). Total volume discharged from the outlet for the week was used to calculate the mass of pollutants for this period.

2.4. Sludge pollutant content and mass balance analysis

Differences between plant species and the unplanted control were assessed using two different approaches: (1) sludge pollutant content, determined by the ratio of pollutants per total sludge solids, and (2) a mass balance analysis, which gives the distribution of water and pollutants in the mesocosms, which allowed us to evaluate the quantity remaining in the sludge cake, plants, and the saturated layer or discharged at the outlet. In addition, substances remaining unaccounted for were assumed to provide an estimate of the percentage of pollutants trapped or mineralised inside the STWs. A very low amount of pollutants (below sampling variation) appeared to be lost over the winter periods and was thus considered negligible.

2.5. Physical and chemical analyses of pollutants

Total solids (TS) and total volatile solids (TVS) were analysed according to Standard Methods (APHA et al., 2012). Total Kjeldahl nitrogen (TKN), total phosphorus (TP) and total carbon (TC) were measured using a QuikChem automated flow injection analyser according to the manufacturer's instructions (QuikChem 8500, Lachat). The percentage TS are reported per wet sludge cake, while TVS, TC, TKN and TP are presented by sludge cake dry total solids (Table 3). For the mass balance analysis, all concentrations of pollutants were multiplied by volume and divided by the surface area of the mesocosm. The mass balance analysis of the sludge cake was calculated by dividing the mass of pollutants present in the core sludge sample by the sampling area (1.5 cm^2). The results are presented in Fig. 2 as the percentage of pollutants per total pollutants added per surface area of STW. This extrapolation of pollutants per surface area of STW was corrected by subtracting the surface area occupied by the plants and aeration pipe in the STWs.

2.6. Water balance analysis

Water balance was estimated only for the summer of 2010, when the plants were well established, by calculating the amount of water in the sludge cake, the water lost by evapotranspiration, the volume present in the saturated layer and the volume discharged at the outlet. The amount of water present in the sludge layer of the STWs was calculated by extrapolating the water content of the core samples (1.5 cm^2) to the surface occupied by the sludge in the STWs. This was done at the beginning of the summer of 2010, to establish the initial water content of the sludge cake, and at the end of the summer. The difference between these values constituted the amount of water retained in the sludge cake for this period, which was expressed as the percentage of water in the sludge cake per total water added (water in sludge + rain) (Fig. 2).

Water loss through evapotranspiration (ET) was calculated weekly by measuring total inlet volume, the variation of volume inside the mesocosms and total outlet volume (Eq. (1)).

$$ET = V_{In} - ((V_{d7} - V_{d1}) + V_{out}) \tag{1}$$

where V_{In} is the inlet volume (sludge + rain volume for the week); V_{d1} is the volume inside the mesocosm, day 1; V_{d7} is the volume inside the mesocosm, day 7; V_{out} is the volume collected from the outlet for the week.

The volume of capillary water in the drained portion of the STWs was not included in the ET calculation, since it can be considered as negligible (Stefanakis and Tsihrintzis, 2011). Average ET ($L m^{-2} d^{-1}$) was calculated as the total volume lost by evapotranspiration divided by the surface of the mesocosm and the 7 days of the week (Table 2). The percentage of water lost by evapotranspiration per total water added during the summer of 2010 is presented in Fig. 2a of the mass balance analysis. The volume of water in the saturated layer at the end of the experiment and the total volume discharged at the outlet of the STWs are also presented as the percentage per total water added in the mass balance analysis. Almost all the water added to the STW was accounted for, with a margin

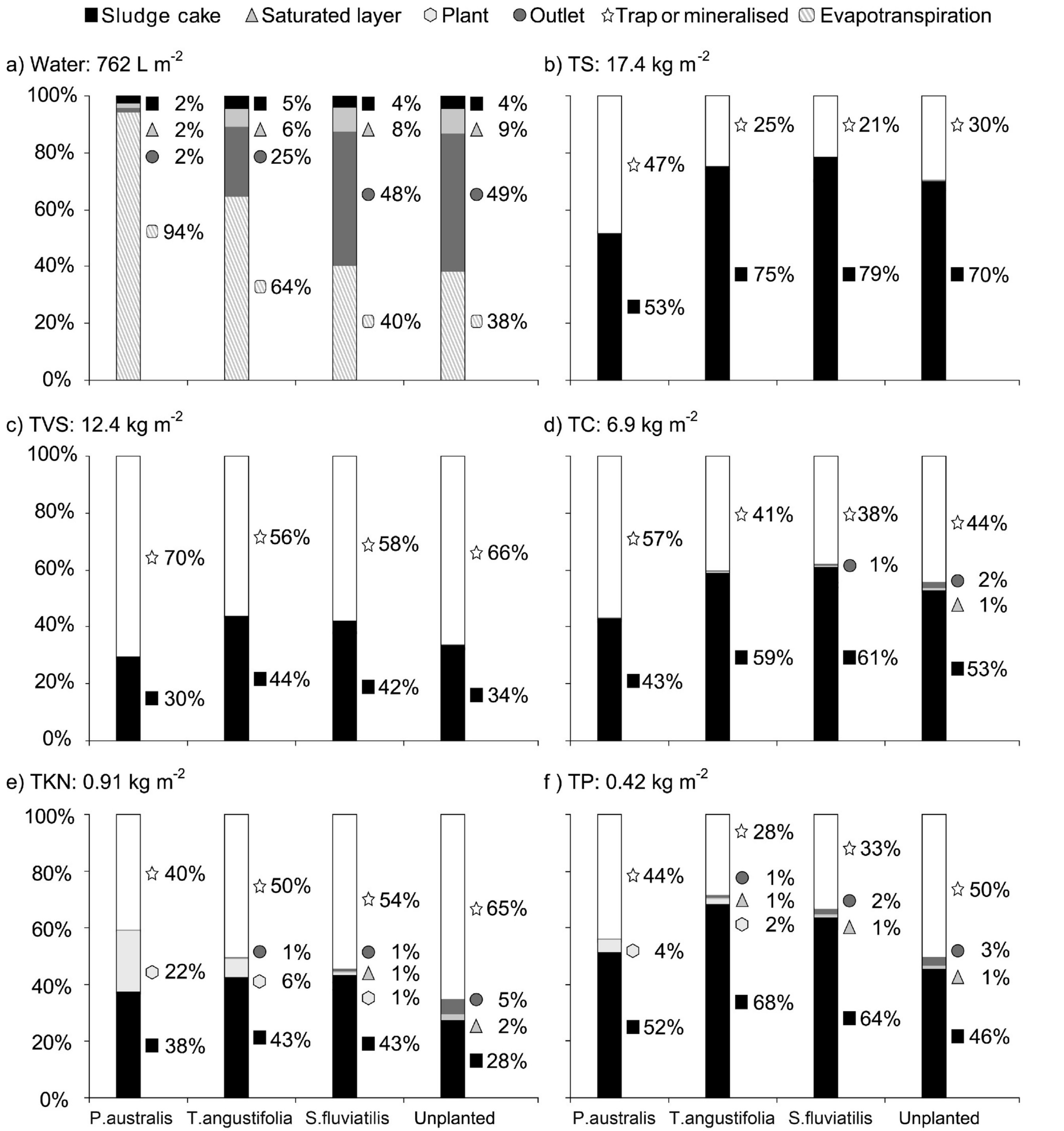

Fig. 2. Mass balances for the fate of water and pollutants for summers 2008–2010 according to plant species: (a) water balance*, (b) total solids, (c) total volatile solids, (d) total carbon, (e) total Kjeldahl nitrogen, and (f) total phosphorus. Percentages below 1% are not presented. *Extra 338 L m^{-2} of water was added to the bottom of *P. australis* STWs (no contact with the sludge cake).

Table 2
Plant biomass, density, and evapotranspiration according to different plant species for summer 2010 (average ± standard deviation).

	Biomass		Plant density	ET
	Above (g m^{-2})	Below* (g m^{-2})	(nb. m^{-2})	(L m^{-2} d^{-1})
P. australis	3087 ± 69	3331	1432 ± 165	10.9 ± 0.6
T. angustifolia	827 ± 331	2183	258 ± 55	5.3 ± 1.3
S. fluviatilis	100 ± 48	453	120 ± 50	3.3 ± 0.6
Unplanted				3.0 ± 1.1

Table 3
Characteristics of raw sludge and of the sludge cake according to different plant species at the end of summer 2010 (average ± standard deviation).

	Volume reduction (%)	TS (%)	TVS (%)	TC (%)	TKN (%)	TP (%)
Sludge		4 ± 2	72 ± 14	39 ± 8	6.4 ± 1.6	2.4 ± 0.9
P. australis	89 ± 1	31 ± 3	40 ± 6	32 ± 2	3.7 ± 0.3	2.3 ± 0.2
T. angustifolia	80 ± 10	28 ± 1	42 ± 6	31 ± 1	3.0 ± 0.4	2.2 ± 0.7
S. fluviatilis	84 ± 1	33 ± 15	39 ± 2	31 ± 2	2.8 ± 0.4	1.9 ± 0.2
Unplanted	85 ± 3	28 ± 5	34 ± 1	30 ± 7	2.1 ± 0.3	1.6 ± 0.2

of error of less than 5%, which was redistributed proportionally to avoid having a total higher than 100%.

2.7. Plant density and nutrients content

At the end of each summer, the number of stems was counted and the above-ground portions were cut, dried and weighed. The measured weight of above-ground biomass was then divided by the surface area of the mesocosms and used to estimate the nutrient uptake by the plants. Below-ground biomass was assessed at the end of the third summer for only one replicate of each species. Half of the volume of each mesocosm was excavated and the rhizome and roots were collected, dried and weighed. The measured mass was then divided by the excavated surface of the mesocosms and used to estimate the nutrient uptake by the plants. Plant uptake of nitrogen and phosphorus was estimated by multiplying dry biomass (above- and below-ground) by the specific nutrients content per dry biomass according to values determined by Tanner et al. (1995), Ennabili et al. (1998) and Smith et al. (2008). Since no phosphorus content was found in the literature for below-ground biomass of *S. fluviatilis*, only above-ground phosphorus content is presented. The amount of nutrients present in plants tissues was expressed in percentage of nutrients per total nutrients added by the sludge. Plant density and biomass at the end of summer 2010 is presented in Table 2, which corresponds to peak plant establishment in the system.

3. Results

3.1. Plant parameters

The plants reached their maximum density, biomass and evapotranspiration during the summer of 2010, with the highest value obtained by *P. australis*, followed by *T. angustifolia* and then *S. fluviatilis* (Table 2). Evapotranspiration rate was low in *S. fluviatilis*, which did not grow well in sludge, and corresponded to the evaporation rate of the unplanted control (Table 2).

3.2. Sludge volume reduction

A total of 0.59 $m^3\,m^{-2}$ of sludge was added to the STWs during the experiment. The highest reduction in sludge volume was measured in *P. australis* STWs, where the sludge cake was reduced to 0.07 $m^3\,m^{-2}$, followed by the unplanted control with 0.09 $m^3\,m^{-2}$, *S. fluviatilis* with 0.09 $m^3\,m^{-2}$ and *T. angustifolia* with 0.12 $m^3\,m^{-2}$ (Table 3).

3.3. Fate of water in STWs

Approximately 762 $L\,m^{-2}$ of water (sludge + rain), was added to the STWs during the summer of 2010, in addition to 338 $L\,m^{-2}$ of tap water which was added at the bottom of *P. australis* STWs (no contact with the sludge cake) to prevent drought and plant mortality. Mass balance analysis revealed that water was mainly evapotranspired in *P. australis* STWs ($1034 \pm 80\,L\,m^{-2}$) and to a lesser extent in *T. angustifolia* ($491 \pm 125\,L\,m^{-2}$), while only $307 \pm 63\,L\,m^{-2}$ of water was lost by evapotranspiration in *S. fluviatilis* and $291 \pm 98\,L\,m^{-2}$ for the unplanted control (Fig. 2a). The water discharged at the STWs outlet showed an inverse pattern, with the lowest value for *P. australis* ($17 \pm 8\,L\,m^{-2}$), followed by *T. angustifolia* ($188 \pm 73\,L\,m^{-2}$), while *S. fluviatilis* and the unplanted STWs had about half of the water input discharged at the outlet (360 ± 0.2 and $371 \pm 118\,L\,m^{-2}$, respectively). The water remaining in the saturated layer of the STWs represented a small fraction of the water input, with $18 \pm 18\,L\,m^{-2}$ for *P. australis* followed by *T. angustifolia* ($48 \pm 24\,L\,m^{-2}$), *S. fluviatilis* ($63 \pm 1\,L\,m^{-2}$) and the unplanted control ($66 \pm 3\,L\,m^{-2}$). The sludge cake of *P. australis* STWs retained the lowest amount of water ($19 \pm 5\,L\,m^{-2}$), while the other plant species and the unplanted control retained about 13 L more water per surface ($34 \pm 2\,L\,m^{-2}$, $33 \pm 6\,L\,m^{-2}$ and $31 \pm 15\,L\,m^{-2}$ for *T. angustifolia*, unplanted and *S. fluviatilis*, respectively).

3.4. Total solids

The TS content (sludge dryness, TS/wet sludge) varied from 4% in the fresh sludge to about 30% in sludge cake of the STWs with no significant difference between plant species or the unplanted STWs (Table 3).

In terms of mass balance, a total of 17.4 $kg\,TS\,m^{-2}$ was added to the STWs during the experiment, and only half of the solids ($9.2 \pm 0.8\,kg\,m^{-2}$) remained in the sludge cake of *P. australis* STWs, while the unplanted ($11.6 \pm 0.9\,kg\,m^{-2}$), *T. angustifolia* ($13.1 \pm 0.4\,kg\,m^{-2}$) and *S. fluviatilis* ($13.6 \pm 0.2\,kg\,m^{-2}$) had higher values (Fig. 2b). The amount of solids present in the saturated layer (0.001–0.003 $kg\,m^{-2}$) and at the outlet of the STWs (0.002–0.020 $kg\,m^{-2}$) was low for all the planted systems. In contrast, the unplanted control had, a higher proportion of solids in the saturated layer (0.013 $kg\,m^{-2}$) and at the outlet of the STWs (0.064 $kg\,m^{-2}$). For all treatments, the remaining solids unaccounted for were considered as trapped or mineralised.

3.5. Total volatile solids

The TVS content (TVS/TS) ranged from 72% in the fresh sludge to about 40% in the sludge cake of the planted systems, which contained some plant litter, while the unplanted controls had the lowest (34%) TVS content (Table 3).

In terms of mass balance, a total of 12.4 $kg\,TVS\,m^{-2}$ was added to the STWs, and at the end of the experiment, most of the TVS was considered trapped or mineralised within the STWs, with a higher fraction in *P. australis* ($8.7 \pm 0.9\,kg\,m^{-2}$), followed by the unplanted ($7.8 \pm 0.5\,kg\,m^{-2}$), *S. fluviatilis* ($7.1 \pm 0.1\,kg\,m^{-2}$) and *T. angustifolia* ($6.9 \pm 1.1\,kg\,m^{-2}$) (Fig. 2c). The remaining volatile solids were retained in the sludge layer, with the lowest amount of volatile solids in the sludge cake of *P. australis* STWs ($3.7 \pm 0.9\,kg\,m^{-2}$), followed by the unplanted ($4.0 \pm 0.5\,kg\,m^{-2}$), *S. fluviatilis* ($5.2 \pm 0.1\,kg\,m^{-2}$) and *T. angustifolia* ($5.4 \pm 1.1\,kg\,m^{-2}$). The amount of volatile solids present in the saturated layer ($\leq 0.001\,kg\,m^{-2}$) and at the outlet of the STWs was low (0.001–0.006 kg m^{-2}) for all planted units. Higher amounts of volatile solids were measured in the saturated layer (0.006 kg m^{-2}) and at the outlet of the unplanted STWs (0.028 kg m^{-2}).

3.6. Total carbon

The TC content (TC/TS) varied from 39% in the fresh sludge to about 30%, with no significant difference between plant species or the unplanted STWs (Table 3).

In terms of mass balance, the carbon added by the sludge represented 6.9 kg TC m^{-2} and was mostly accumulated in the sludge cake, with a lower faction present in *P. australis* (3.0 ± 0.4 kg m^{-2}), followed by the unplanted (3.5 ± 0.5 kg m^{-2}), *T. angustifolia* (4.1 ± 0.2 kg m^{-2}) and *S. fluviatilis* (4.2 ± 0.2 kg m^{-2}) (Fig. 2d). The rest of the carbon was generally trapped or mineralised in *P. australis* STWs (3.9 ± 0.4 kg m^{-2}), followed by the unplanted (2.9 ± 0.4 kg m^{-2}), *T. angustifolia* (2.8 ± 0.2 kg m^{-2}) and *S. fluviatilis* (2.6 ± 0.2 kg m^{-2}). Only a small fraction of the carbon was present in the saturated layer of the planted systems (0.01–0.03 kg m^{-2}), with a slightly higher value for the unplanted controls (0.05 kg m^{-2}). The carbon at the outlet followed a similar pattern, with 0.01–0.05 kg m^{-2} discharged by planted STWs and 0.14 kg m^{-2} for the unplanted control.

3.7. Total Kjeldahl nitrogen

The TKN content (TKN/TS) dropped from 6.4% in the fresh sludge to 3.7% in the sludge cake of *P. australis* STWs, followed by *T. angustifolia* with 3.0% and *S. fluviatilis* with 2.8%, while the control had the lowest percentage of nitrogen, with 2.1% (Table 3).

In terms of mass balance, the nitrogen added by the fresh sludge represented 0.91 kg TKN m^{-2} and most of it was trapped or mineralised in the unplanted control (0.56 ± 0.06 kg m^{-2}), followed by *S. fluviatilis* (0.50 ± 0.07 kg m^{-2}), *T. angustifolia* (0.46 ± 0.05 kg m^{-2}) and *P. australis* (0.37 ± 0.06 kg m^{-2}) (Fig. 2e). The remaining nitrogen was generally found in the sludge cake, with a lower proportion in the unplanted control (0.24 ± 0.06 kg m^{-2}), followed by *P. australis* STWs (0.34 ± 0.05 kg m^{-2}), *S. fluviatilis* (0.39 ± 0.07 kg m^{-2}) and *T. angustifolia* (0.39 ± 0.05 kg m^{-2}). Part of the nitrogen was also sequestered in plant tissues, with close to a quarter (0.196 ± 0.003 kg m^{-2}) of the total nitrogen in *P. australis*, followed by *T. angustifolia* (0.057 ± 0.003 kg m^{-2}) and *S. fluviatilis* STWs (0.007 ± 0.001 kg m^{-2}). Low quantities of nitrogen were present in the saturated layer of the planted STWs (0.001–0.005 kg m^{-2}), with a higher amount in the unplanted control (0.017 kg m^{-2}). The fraction of nitrogen at the outlet was low in the planted STWs (0.002–0.009 kg m^{-2}), but significantly higher for the unplanted control (0.046 kg m^{-2}).

3.8. Total phosphorus

The TP content (TP/TS) decreased only slightly, from 2.4% in the fresh sludge to 2.3% in the *P. australis* sludge cake, followed by *T. angustifolia* with 2.2% and *S. fluviatilis* with 1.9%. The sludge cake of the unplanted control had a content of 1.6% of TP per dry solids (Table 3).

In terms of mass balance, phosphorus added by the fresh sludge (0.42 kg TP m^{-2}) was generally retained in the sludge cake, with a higher amount in *T. angustifolia* (0.29 ± 0.09 kg m^{-2}), followed by *S. fluviatilis* (0.27 ± 0.04 kg m^{-2}), *P. australis* (0.22 ± 0.03 kg m^{-2}), and finally the unplanted control (0.18 ± 0.04 kg m^{-2}) (Fig. 2f). The rest was mainly considered as trapped or mineralised in the STWs. A small fraction of the phosphorus was sequestered in plant tissues, with 0.018 kg m^{-2} for *P. australis*, 0.007 kg m^{-2} for *T. angustifolia* and 0.001 kg m^{-2} for *S. fluviatilis*. A very small amount of the sludge phosphorus was present in the saturated layer (0.001–0.004 kg m^{-2}) of the STWs. Very little phosphorus reached the outlet of the STWs, with a value between 0.001 and 0.008 kg m^{-2} in the planted systems and 0.013 kg m^{-2} at the outlet of the unplanted controls.

4. Discussion

Sludge pollutants were mainly retained within the sludge cake at the surface of the STWs, and the remainder was generally trapped inside the STWs or transformed into minerals, gas and water. In addition, a fraction of nitrogen and phosphorus of varying amounts, depending on the plant species, was sequestered in the plant biomass. Finally, only a very small percentage of the pollutants added by the sludge were present in the saturated layer or were discharged at the outlet of the STWs (Fig. 2). The low percentage of pollutants discharged can be explained by the efficient physical filtration provided by the system and by the fact that the STWs were not completely drained, thus favouring evapotranspiration and a longer contact time between the pollutants and the plant rhizosphere. The presence of a partly saturated layer in our STWs, which distinguished them from STWs drained by usual methods, did not seem to affect sludge dewatering or mineralisation, but had a favourable influence on water quality at the outlet. A detailed account of the effect of plant species on water quality is presented in Gagnon et al. (2012). The effect of plant species on the sludge cake is complex, since it acts both on the content (ratio) and on the total amount of water and pollutants present. The following section examines the specific influence of plant species on dewatering and mineralisation.

4.1. Sludge volume reduction and dewatering

Sludge treatment wetlands planted with *P. australis* had the highest sludge volume reduction and were the most efficient in sludge dewatering based on mass balance analysis (Table 2, Fig. 2a and b). Sludge volume reductions varied between 80 and 89% depending on plant species, which is in the range reported in the literature (81–98%) for STWs (Cooper et al., 2004). The difference in sludge volume reduction between *P. australis* and the unplanted control (4%) is in the 3–8% range reported in the literature (Edwards et al., 2001; Stefanakis and Tsihrintzis, 2011). The lower amount of water per surface in the sludge cake of *P. australis* (Fig. 2a) can be partly explained by the very high evapotranspiration rate of *P. australis*, 2–3.5 times higher than for *T. angustifolia* and *S. fluviatilis*, respectively (Table 2). The percentage of water lost by evapotranspiration in *P. australis* (94%) and *T. angustifolia* (64%) was higher than reported in the literature for similar sized systems, with a maximum of 84% in *P. australis* and 42% in *T. angustifolia* (Panuvatvanich et al., 2009; Stefanakis and Tsihrintzis, 2011). This could be explained by the fact that our STWs was not completely drained, thus enhancing evapotranspiration, but could also be due to the lower volume of sludge applied in our experiment (Gagnon et al., 2012). Furthermore, *P. australis* had by far the highest plant density, which riddled the sludge cake with tunnels produced as the plants moved in the wind, creating a void in the sludge around the stem. These tunnels are thought to favour the drainage and aeration of the sludge cake, and consequently the dewatering and mineralisation processes (Nielsen, 2003). Nonetheless, the relatively small size of the experimental mesocosm (0.28 m^2) could have also promoted higher evapotranspiration rate via the “oasis” and “clothesline” effects (Allen et al., 2011). Therefore, further studies should be done to assess the influence of plants and species in full size systems.

Mass balance analyses revealed that the sludge cake of *P. australis* had on average 3.6 kg less dry solids and 13 L less water per surface compared to the other STWs (Fig. 2a and b), indicating a higher dewatering. However, the solids content of the sludge cake did not differ between plant species and the unplanted control, with about 30% of solids, which is in the range (20–30%) for STWs planted with *P. australis* (Uggetti et al., 2010). This absence of difference between plant species concurs with the results obtained by Uggetti et al. (2012). At first glance, this seems to contradict the results of the mass balance analysis, but can be explained by the fact that the solids content represents a ratio (dry/wet sludge) and not the physical amount of solids or water present in the sludge layer. Thus the sludge cake of *P. australis* had the same ratio of solids and water as the other STWs, but a lower absolute amount of solids and water per surface of STW in terms of mass. Therefore, our results indicate that the use of a mass balance analysis is a more adequate method when comparing the effect of plant species, since it represents a quantitative measurement of pollutants, compared to the pollutants content (ratio) which is relative and thus unreliable for a precise comparison. This concept is also true for the organic matter (TVS) and the nutrients (N, P) content of the sludge cake. Nonetheless, pollutant content of the sludge will be compared to the results from the literature, since it is the current method of data analysis.

4.2. Sludge mineralisation

Higher sludge volume reduction in *P. australis* can also be attributed to enhanced mineralisation of the organic matter (Nielsen, 2003), where part of the solids is transformed into simpler compounds such as minerals, gas and water. Higher mineralisation in *P. australis* STWs is shown in the mass balance by the lower amount of solids, volatile solids and carbon per surface compared to the other plant species and, to a lesser extent, to the unplanted control. This could be explained by the enhancement of microbial activity favoured by better aeration of the sludge cake in *P. australis* STWs (Wang et al., 2012). However, a slightly higher amount of organic matter per surface of wetland was measured in the *T. angustifolia* and *S. fluviatilis* sludge cake when compared to the unplanted control. This could be due to the presence of plant litter within the sludge (Hofmann, 1990), fragments of which were clearly visible within the sludge samples, even though plants were harvested at the end of each summer. Thus, the addition of organic matter by the plant litter could have mitigated the mineralisation process for *T. angustifolia* and *S. fluviatilis*, but had a lesser impact on *P. australis* STWs, where the litter fell on a highly mineralised sludge cake. This concept is supported by the greater volatile solids content in the sludge cake of the planted STWs (39–42%), which was in the same range as reported in the literature (40–50%) (Uggetti et al., 2010) for planted STWs, and slightly lower for the unplanted control (34%). We would have expected a higher amount of carbon content in the sludge cake of the planted systems, due to the addition of carbon from the plant litter. If the percentage of total carbon per solids in the sludge cake did not vary according to plant species or in the unplanted control, the mass balance analysis shows that the total amount of carbon is greater in *T. angustifolia* and *S. fluviatilis*, compared to control.

Planted systems tended to retain a higher mass of nutrients (TKN and TP), and at a higher content, in the sludge cake when compared to the unplanted control. This could be attributed to the added plant litter, which returned part of the nutrients back to the sludge cake. Nonetheless, the reduction of nitrogen content per solids was very similar to results obtained by Uggetti et al. (2012), who reported a nitrogen content of 3.9% and 3.4% in the sludge cake of *P. australis* and *T. angustifolia* respectively, when loaded with fresh sludge containing about 6.7% of TKN/TS. However, in terms of percentage of phosphorus in the sludge cake, Uggetti et al. (2012) found a net decrease, the percentage present in fresh sludge dropping from about 2.5% TP/TS to 0.14% and 0.02% in *P. australis* and *T. angustifolia*. By comparison, our study showed that the phosphorus in the sludge cake did not change significantly, with 2.3% and 2.2% of TP/TS in *P. australis* and *T. angustifolia* respectively when fed with fresh sludge at 2.4% TP/TS. The discrepancies between the two studies may be explained by the form of phosphorus present in the sludge, which was mainly organic in this study. Nonetheless, the higher percentage of phosphorus per solids can be considered a positive outcome, since it adds fertilizing quality to the sludge residue and limits discharge into the environment.

Nitrogen mineralization was efficient in STWs, where 40–65% of the total nitrogen input by the sludge was considered as trapped or mineralised in the planted and unplanted STWs. In planted STWs, nitrogen is thought to have been mainly mineralised into nitrogen gas, with the sequential process of ammonification in the sludge layer, followed by nitrification in the aerated sludge and through the oxygenated root zone, and finally denitrification in the saturated part of the STWs (Faulwetter et al., 2009). In addition, plants sequestered a fraction of nitrogen in their tissues, at a level particularly significant in *P. australis*, with up to 22% of the total nitrogen input by sludge. Similar results were found by Korboulewsky et al. (2012), with a total of 23% of nitrogen input by sludge in *P. australis* biomass. However, the unplanted STWs had limited nitrification due to the lack of available oxygen, which resulted in an accumulation of ammonia in saturated layers and prevented the removal of nitrogen through denitrification (Gagnon et al., 2012). Nonetheless, mass balance analysis revealed that the unplanted control had the highest percentage of nitrogen unaccounted for, which was considered trapped or mineralised in the STWs. This high reduction in nitrogen may be the result of ammonia volatilisation in unplanted systems, in which the transformation of the ammonium ion to ammonia gas is favoured under a pH greater than 7, warm temperatures and high ammonium concentration (Jayaweera and Mikkelsen, 1991). Unplanted STWs had a high level of ammonium and possibly a high pH, which was not measured, but would explain the loss of nitrogen through volatilisation.

Phosphorus was mainly retained in the sludge in the planted system (52–68%) and, to a lesser extent, in the unplanted control (46%). The remaining phosphorus was considered trapped or transformed from organic into inorganic forms in the sludge layer and leached to the saturated layer of the STWs, where it was probably adsorbed or precipitated on calcium, aluminium or iron present in the gravel media. The higher amount of phosphorus trapped inside the unplanted STWs (53%) could be also explained by higher pH which would have favoured the formation of calcium-phosphate precipitates. However, this is a hypothesis, since pH or phosphate precipitates were not measured in this experiment.

5. Conclusion

The fate of pollutants in sludge treatment wetlands was mainly characterised by their retention within the sludge cake, with remaining pollutants generally considered as trapped inside the STWs or transformed into minerals, gas and water. A fraction of the nitrogen and phosphorus was sequestered in plant tissues, representing close to a quarter of the nitrogen input by the sludge in *P. australis* STWs. Only a very small percentage of the pollutants was discharged at the outlet, due to the good physical filtration of the system and the fact that the STWs were not completely drained which favoured pollutants removal. Plant species had a distinct effect on the sludge cake, with lower performance in *T. angustifolia* and *S. fluviatilis* STWs, while *P. australis australis*, STWs exhibited the highest sludge volume reduction and the best sludge dewatering and mineralisation, as determined by a mass balance analysis. This was explained by *P. australis*' high evapotranspiration rate and plant density, which created tunnels in the sludge cake and favoured sludge drainage and aeration. However, the sludge cake of the planted systems had a higher mass and nutrients content than the unplanted STWs, possibly due to the presence of plant litter in the sludge cake, which is not necessarily a negative finding, since the nutrients retained in the sludge cake could be used as fertilisers.

This research indicates that using a mass balance analysis is a more adequate method when comparing the effect of plant species, since it represents a quantitative measurement of pollutants, compared to the pollutant content of the sludge which is unreliable when a precise comparison is needed. Nonetheless, the measurement of pollutants content is still a useful method to assess large variations, such as the difference between the fresh sludge (TS: 3%) and the pollutant content of the sludge cake (TS: 30%) at the surface of the STW.

Further studies should be done to assess the influence of plants presence and species in full size STWs to validate the finding obtained in this mesocosm experiment.

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References

Allen, R.G., Pereira, L.S., Howell, T.A., Jensen, M.E., 2011. Evapotranspiration information reporting. I. Factors governing measurement accuracy. Agric. Water Manage. 98 (6), 899–920.

APHA, AWWA, WEF, 2012. Standard Methods for the Examination of Water and Wastewater, 22nd ed. American Public Health Association/American Water Works Association, Water Environment Federationf, Washington, DC.

Begg, J.S., Lavigne, R.L., Veneman, P.L.M., 2001. Reed beds: constructed wetlands for municipal wastewater treatment plant sludge dewatering. Water Sci. Technol. 44 (11–12), 393–398.

Clarke, E., Baldwin, A.H., 2002. Responses of wetland plants to ammonia and water level. Ecol. Eng. 18 (3), 257–264.

Cooper, P., Willoughby, N., Cooper, D., 2004. The use of reed-beds for sludge drying. Water Environ. J. 18 (2), 85–89.

Edwards, J.K., Gray, K.R., Cooper, D.J., Biddlestone, A.J., Willoughby, N., 2001. Reed bed dewatering of agricultural sludges and slurries. Water Sci. Technol. 44 (11–12), 551–558.

Ennabili, A., Ater, M., Radoux, M., 1998. Biomass production and NPK retention in macrophytes from wetlands of the Tingitan Peninsula. Aquat. Bot. 62 (1), 45–56.

Environment Canada, Climate Normals 1971–2000. National Climate Data and Information Archive Website. www.climate.weatheroffice.gc.ca/climate_normals/index_e.html (accessed on May 16, 2012).

Faulwetter, J.L., Gagnon, V., Sundberg, C., Chazarenc, F., Burr, M.D., Brisson, J., Camper, A.K., Stein, O.R., 2009. Microbial processes influencing performance of treatment wetlands: a review. Ecol. Eng. 35 (6), 987–1004.

Gagnon, V., Chazarenc, F., Koiv, M., Brisson, J., 2012. Effect of plant species on water quality at the outlet of a sludge treatment wetland. Water Res. 46 (16), 5305–5315.

Hofmann, K., 1990. Use of phragmites in sewage sludge treatment. In: Cooper, P.F., Findlater, B.C. (Eds.), Constructed Wetlands in Water Pollution Control. , pp. 269–277.

Jayaweera, Mikkelsen, 1991. In: Brady, N.C. (Ed.), Advances in Agronomy, vol. 45. Academic Press, San Diego, California.

Koottatep, T., Polprasert, C., Oanh, N.T.K., Heinss, U., Montangero, A., Strauss, M., 2001. Septage dewatering in vertical-flow constructed wetlands located in the tropics. Water Sci. Technol. 44 (2–3), 181–188.

Korboulewsky, N., Wang, R., Baldy, V., 2012. Purification processes involved in sludge treatment by a vertical flow wetland system: focus on the role of the substrate and plants on N and P removal. Bioresour. Technol. 105, 9–14.

Liénard, A., Duchène, P., Gorini, D., 1995. A study of activated sludge dewatering in experimental reed-planted or unplanted sludge drying beds. Water Sci. Technol. 32 (3), 251–261.

Naylor, S.J., Moccia, R.D., Durant, G.M., 1999. The chemical composition of settleable solid fish waste (manure) from commercial rainbow trout farms in Ontario, Canada. North Am. J. Aquacult. 61 (1), 21–26.

Nielsen, S., 2003. Sludge drying reed beds. Water Sci. Technol. 48 (5), 101–109.

Nielsen, S., 2007. Helsinge sludge reed bed system: reduction of pathogenic microorganisms. Water Sci. Technol. 56 (3), 175–182.

Panuvatvanich, A., Koottatep, T., Kone, D., 2009. Influence of sand layer depth and percolate impounding regime on nitrogen transformation in vertical-flow constructed wetlands treating faecal sludge. Water Res. 43 (10), 2623–2630.

Smith, K.E., Schwab, A.P., Banks, M.K., 2008. Dissipation of PAHs in saturated, dredged sediments: a field trial. Chemosphere 72 (10), 1614–1619.

Stefanakis, A.I., Tsihrintzis, V.A., 2011. Dewatering mechanisms in pilot-scale sludge drying reed beds: effect of design and operational parameters. Chem. Eng. J. 172 (1), 430–443.

Stefanakis, A.I., Tsihrintzis, V.A., 2012. Effect of various design and operation parameters on performance of pilot-scale sludge drying reed beds. Ecol. Eng. 38 (1), 65–78.

Tanner, C.C., Clayton, J.S., Upsdell, M.P., 1995. Effect of loading rate and planting on treatment of dairy farm wastewaters in constructed wetlands. 2. Removal of nitrogen and phosphorus. Water Res. 29 (1), 27–34.

Troesch, S., Liénard, A., Molle, P., Merlin, G., Esser, D., 2009. Treatment of septage in sludge drying reed beds: a case study on pilot-scale beds. Water Sci. Technol. 60 (3), 643–653.

Uggetti, E., Ferrer, I., Carretero, J., García, J., 2012. Performance of sludge treatment wetlands using different plant species and porous media. J. Hazard. Mater. 217–218, 263–270.

Uggetti, E., Ferrer, I., Llorens, E., García, J., 2010. Sludge treatment wetlands: a review on the state of the art. Bioresour. Technol. 101 (9), 2905–2912.

Vincent, J., Molle, P., Wisniewski, C., Liénard, A., 2011. Sludge drying reed beds for septage treatment: towards design and operation recommendations. Bioresour. Technol. 102 (17), 8327–8330.

Wang, R., Baldy, V., Périssol, C., Korboulewsky, N., 2012. Influence of plants on microbial activity in a vertical-downflow wetland system treating waste activated sludge with high organic matter concentrations. J. Environ. Manage. 95 (Suppl.), S158–S164.