Performance of a French system of vertical flow wetlands (first stage) operating with an extended feeding cycle

Camila Maria Trein, Jorge Alejandro García Zumalacarregui, Mirene Augusta de Andrade Moraes and Marcos von Sperling

ABSTRACT

The aim of this work was to evaluate the treatment performance in the first stage of a vertical flow constructed wetland – French system (VCW-FS) over an extended feeding period (seven days), in two parallel units, for a population equivalent (p.e.) around 100 inhabitants (total of 0.6 $m^2 \cdot p.e.^{-1}$), under Brazilian tropical climatic conditions. One of the units had a greater surface sludge deposit layer, accumulated over nine years of operation, while the other unit had its sludge removed prior to the experiments. Four intensive monitoring campaigns covering all days of the feeding cycle were undertaken and the results were compared with those obtained from the conventional monitoring. The results indicated that, over the days of the feeding cycle, dissolved oxygen concentrations decreased, but were still kept at sufficiently high values for the removal of organic matter. Therefore, chemical oxygen demand (COD) removal, although not high, remained acceptable for compliance with local discharge standards during the whole the period. The NH_4^+-N removal efficiency and NO_3^--N production were higher at the beginning of the feeding cycle, as a result of the more well-established aerobic conditions, with the nitrification rate decreasing from the third day of feeding. The sludge deposit seemed to hinder liquid percolation, especially at the end of the feeding cycle, thus affecting oxygen transfer. Due to the variability of the results over the feeding cycle, if sampling is to be done once a week, it is important to identify the sampling day that best represents the system's performance.

Key words | developing countries, organic deposit layer, oxygen transfer, raw sewage treatment, treatment wetlands

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INTRODUCTION

Among the vertical downflow variants of constructed wetlands, a major one is represented by the so-called French system (VCW-FS), which is the only type that is used to treat raw sewage (Fonder & Headley 2013). The traditional configuration of VCW-FS comprises two treatment steps. The first stage has three units in parallel ($1.2\ m^2 \cdot p.e.^{-1}$) with alternating feeding and resting cycles, and has as the main objective the removal of organic matter and suspended solids. The second stage comprises two units ($0.8\ m^2 \cdot p.e.^{-1}$), complementing the treatment, mainly aiming at ammonia removal (Molle *et al.* 2005).

In countries that do not have very strict discharge standards, only the first stage of the VCW-FS may be sufficient (Lombard Latune & Molle 2017). The land requirements may be even lower in tropical climatic conditions that are favourable to biological processes. According to Lombard Latune & Molle (2017), good treatment capacity may be maintained with only two units in parallel in the first stage.

Several mechanisms take place in the system, such as filtration, sedimentation and microbiological degradation (Cooper *et al.* 1996). These processes occur in an operational cycle of feeding and resting. The feeding and resting periods should be effective in controlling bacterial growth and maintaining aerobic conditions in the filter. They should also be effective in allowing the mineralization of the organic matter present in the raw sewage solids, which are retained and accumulated on the surface of the units, creating an upper layer of sediments (Molle *et al.* 2005). With three units in the first stage, the traditional recommendation is to alternate the units with three and a half days of feeding and seven days of resting (Molle *et al.* 2005). With only two units in parallel, the French recommendations, based

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on a limited number of surveyed tropical systems, is for three and a half days for feeding and the same time for resting (Lombard Latune & Molle 2017).

The duration of the feeding and resting periods influences the hydraulic performance and the removal efficiency, which is reflected directly in the durability and reliability of the system over its operational life (Torrens *et al.* 2009). The alternation of units is considered a minimum operating requirement to ensure proper filter operation. The absence of alternation, or uncontrolled alternation over one year of operation, resulted in the collapse of a VCW-FS installed on the island of Mayotte. After sludge removal and control of the operation, the units showed a rapid resilience, recovering nitrification within a few days, due to the country's tropical climatic conditions (Molle *et al.* 2015).

According to Torrens *et al.* (2009), although their investigation was with a slightly different configuration (vertical flow systems, second stage, fed with pond effluents and using sand as filtering material), a feeding period longer than eight days and/or a short resting period (three and four days) was recognized as a leading cause of clogging of the VCW in France. In their studies, clogging was not observed when the traditional recommended criterion of three and a half days of feeding and seven days of resting was followed. Shorter feeding periods could be acceptable under conditions of hydraulic overloading, such as during rainy periods. For this condition, Arias Lopez (2013) recommends alternating feeding of the units every 100 pulses, as a way of avoiding floods that impair oxygen renewal.

Stefanakis & Tsihrintzis (2012), when comparing resting periods of four, six and eight days, mention that, for organic matter decomposition, a period of four days of resting may be sufficient. However, when the goal is to improve the nitrification process, better removal efficiencies of NH_4^+-N are obtained with a longer resting period.

In order to facilitate operation in large-scale treatment plants, the alternation of the feeding of the units may be performed once a week, with seven days of feeding and 14 days of resting (Prigent *et al.* 2013). However, the authors point out that the nitrification rate eventually decreases from the third feeding day, due to the oxygen decrease in the medium, indicating the need for alternation of the units twice a week, i.e. three and a half days of feeding and seven days of resting.

Taking into account the diversity of experiences found in the literature, coupled with relatively scarce studies covering the duration of the feeding period, especially under tropical climatic conditions, the objective of this study was to evaluate the filter dynamics over an extended feeding cycle (seven days) using only two units in parallel. In this specific research, the heights of the sludge deposit was different in the two units, which assisted in the evaluation of its influence on the performance. Finally, based on the change in performance over the seven days, a discussion on the best day to collect representative samples in monitoring programmes based on weekly samplings was also included.

MATERIAL AND METHODS

Site description

The treatment plant, comprising only the first stage of the French system, is located in Belo Horizonte city, Brazil (latitude 19°53′42″S and longitude 43°52′42″W), at the Centre for Research and Training in Sanitation of the Federal University of Minas Gerais and the Water and Sanitation Company (COPASA). The area has a tropical climate, with an average air temperature of 21.8 °C and annual rainfall of 1,602 mm·year^{-1} (INMET 2018).

The VCW-FS (Figure 1) was designed to treat wastewater generated by a p.e. of 100 inhabitants (average flow of 13 m^3·d^{-1}) following, with some constructive adaptations, the French recommendations from the Institut National de Recherche en Sciences et Technologies pour l'Environnement et l'Agriculture – IRSTEA (previously CEMAGREF). The first stage was originally built with three filter beds, each with a surface area of 29.1 m^2 (3.1 m wide and 9.4 m long), giving a total of 87.3 m^2 (approximately 0.9 m^2·p.e.$^{-1}$). As part of this research, only two units were in operation (representing a total of 0.6 m^2·p.e.$^{-1}$), with one of the units receiving raw sewage for one week, while the other unit was left to rest during that period (total cycle of seven + seven = 14 days). The influent was typical urban wastewater, and underwent only preliminary treatment (coarse, medium and fine screening followed by grit removal) prior to the biological stage.

The influent flow was controlled at the inlet of the system at approximately 13 m^3·d^{-1}. Feeding of the influent on the surface of the wetland was intermittent and hourly, giving 24 pulses·d^{-1} of 0.53 m^3 each, resulting in a mean surface hydraulic loading rate (HLR) in the unit in operation of 0.45 m^3·m^{-2}·d^{-1}, above the French specification of 0.37 m·m^{-2} d^{-1} (Molle *et al.* 2005; Morvannou *et al.* 2015). However, we should note that this hydraulic loading is distributed over only two units in parallel (total HLR over the system equal to

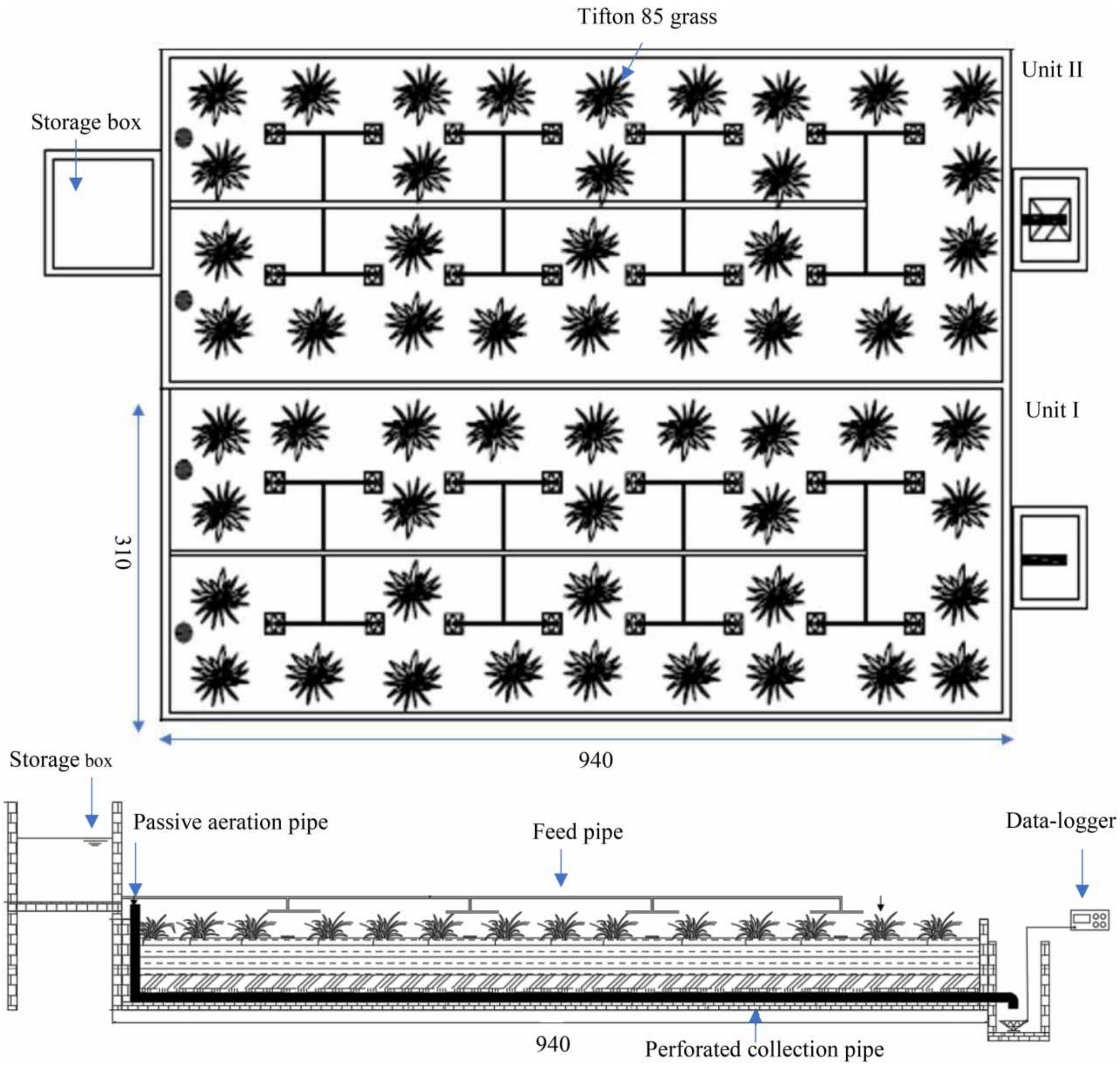

Figure 1 | First stage of the vertical constructed wetland (French system) studied. Dimensions in cm.

$0.45/2 = 0.23\ m^3{\cdot}m^{-2}\ d^{-1}$), much higher than the total HLR recommended in France, for three units ($0.37/3 = 0.12\ m^3{\cdot}m^{-2}\ d^{-1}$). The resulting instantaneous hydraulic loading rate during the 5.5 minutes of the pulse application was $0.20\ m^3{\cdot}m^{-2}{\cdot}h^{-1}$ ($3.3\ L{\cdot}m^{-2}{\cdot}min^{-1}$), lower than the French recommendations.

The units were filled with 15 cm of gravel #3 (19–50 mm) in the drainage zone (bottom), 15 cm of gravel #1 (4.8–25 mm) in the middle layer and 40 cm of gravel #0 (2.4–12.5 mm) in the top layer. Both units were planted with Tifton 85 grass (*Cynodon dactylon* Pers.).

From the start of the operation (2009), one of the units (unit I) accumulated sludge on the surface of the system, as part of the normal operation. In February 2017, the sludge deposited on the surface of unit II was removed in order to support this research on the influence of the sediment layer on the treatment performance. The root system of Tifton 85 grass was left in place. Cutting the aerial part of the plants was done on a routine basis at intervals of 45–60 days. During this study, the height of sludge in unit I was approximately 7.2 cm and in unit II around 0.5 cm. Further details of sludge removal in unit II and the methodology for measuring the height of the spatially accumulated sludge on the surface of the units can be found in Trein *et al.* (2018).

Conventional monitoring over 22 months

A long-term conventional monitoring, comprising almost two years (February 2017–December 2018) was performed routinely on a weekly basis. Samples from the influent and effluent of the two units were collected on the third day of the operational feeding cycle. The selection of the third day was partially because of practical logistical aspects, in order to combine sampling with other treatment systems located in the same research centre. Additionally, this was a better measure of mid-cycle performance, and could also allow comparison with the majority of other systems which operate with feeding cycles of three and a half days. The samples were analysed in terms of pH, temperature, dissolved oxygen (DO), chemical oxygen demand (COD), total suspend solids (TSS), total Kjeldahl nitrogen (TKN), ammonia nitrogen (NH_4^+-N), nitrite nitrogen (NO_2^--N) and nitrate nitrogen (NO_3^--N), following recommendations from *Standard Methods* (APHA/AWWA/WEF 2012).

Intensive monitoring along the days of the feeding cycle

Besides the conventional monitoring, intensive monitoring of the influent and effluent quality was carried out over all the operating days during the feeding period (seven days) in four specific sampling campaigns (two in unit I and two in unit II). All samplings were conducted in the morning, with effluent composite samples (collected each five minutes) proportional to the outflow of one pulse. The campaigns proceeded as follows: unit I (with top sludge): (Ia) 16/03/2017 until 22/03/2017 and (Ib) 26/06/2018 until 03/07/2018; unit II (with sludge previously removed): (IIa) 25/07/2017 until 01/08/2017 and (IIb) 29/08/2017 until 05/09/2017. No rainfall took place in the monitoring days, and mean monthly air temperatures varied from 18 to 23 °C. Because of unaccounted-for problems, it was not possible to collect samples on two days of the last monitoring campaign in unit I (with top sludge). However, it is assumed that these missing data did not affect the evaluation of the behaviour of the system. For logistical reasons it was not possible to perform more intensive monitoring campaigns. Nevertheless, based on the already long operating time of the units (more than eight years), it is believed that the system was already mature and would not show substantial variations during the study period of two years of this particular research.

Statistical analysis

Statistical analyses for the comparison between the units 'with top sludge layer' and 'with sludge layer previously removed' were performed using the non-parametric Mann-Whitney test for independent samples at 5% significance level, using Statistica 10 software.

RESULTS AND DISCUSSION

Treatment performance based on conventional monitoring over 22 months

Long-term monitoring allows a good understanding of the behaviour of a treatment system. The treatment capacity changes with the number of years of operation, influenced by the physical, chemical and biological processes, with an emphasis on the deposit layer accumulated on the surface of the units. The evolution of the sludge layer thickness leads to a better solids filtration efficiency and improved retention and liquid distribution on the surface, favours the adsorption of organic matter and other constituents and promotes a more favourable condition for greater biological activity (Molle 2014).

The operation time influences the sludge deposit characteristics, and wetlands with more than three years of operation can be classified as mature systems (Kania *et al.* 2019). According to Paing *et al.* (2015), a system requires one to two years of operation to accumulate sludge, so that it works as a filtration matrix leading to the best performance in terms of pollutant removal. The system in this study had more than eight years of operation, which led to the idea of removing the sludge deposit from the surface of one of the units (unit II) to allow a comparison of the influence of this deposit layer on the treatment performance.

The main characteristics (number of samples, effluent concentration medians and coefficients of variation, removal efficiency) of the parameters analysed during the period of conventional monitoring (February 2017 to December 2018, a total of 22 months) are summarized in Table 1. Figure 2 presents the box-plots of influent and effluent concentrations, and the overall interpretation of the results is made in the following subsections. It should be remembered that the conventional monitoring was undertaken on a weekly basis, with the samples collected on the third day of feeding.

Influent concentrations are within the typical range indicated by von Sperling (2007) for Brazilian conditions.

Table 1 | Effluent characterization based on conventional monitoring (February 2017–December 2018), covering unit I (with top sludge) and unit II (with sludge previously removed)

Parameter	Unit I (with top sludge) *n*	Median	C.V.	Removal efficiency (%)	Unit II (with sludge previously removed) *n*	Median	C.V.	Removal efficiency (%)
Temperature (°C)	26	26.0	0.30	–	26	25.9	0.34	–
pH	29	7.0	0.08	–	25	7.1	0.32	–
DO ($mg{\cdot}L^{-1}$)*	21	3.4	0.40	–	24	4.60	0.22	–
COD ($mg{\cdot}L^{-1}$)	28	157	0.41	60	19	130	0.33	63
TSS ($mg{\cdot}L^{-1}$)*	24	58	0.77	84	21	69	0.38	76
TKN ($mg{\cdot}L^{-1}$)	28	17.6	0.52	60	24	17.2	0.41	54
NH_4^+-N ($mg{\cdot}L^{-1}$)	28	14.6	0.44	54	24	15.2	0.38	59
NO_2^--N ($mg{\cdot}L^{-1}$)	26	0.1	0.86	–	21	0.1	0.90	–
NO_3^--N ($mg{\cdot}L^{-1}$)	23	17.4	0.74	–	21	14.1	0.85	–
TN ($mg{\cdot}L^{-1}$)	21	35.7	0.4	–	20	31.5	0.5	–

n, number of samples.
C.V. = coefficient of variation = standard deviation/mean.
Removal efficiency (%) = 100 × (influent median – effluent median)/influent median.
*Significantly different ($p < 0.05$) in Mann-Whitney *U*-test.

Compared to European practice (Molle *et al.* 2005; Morvannou *et al.* 2017), the sewage in this study is more diluted, with lower concentrations of organic matter and TKN. In Brazil, lower influent concentrations are generally found in large cities (as is the case here), compared with small towns in rural areas (von Sperling 2007).

The prevailing high liquid temperature (26 °C) indicated favourable conditions for biological treatment. The mean values of the influent pH of unit I and II were 7.3 and 7.2, respectively. In the effluent, the pH decreased slightly, possibly associated with the partial nitrification that took place. Dissolved oxygen increased in both units, with significantly higher values found in the unit with a smaller deposit layer (unit II), indicating that this layer is responsible for a decrease in the oxygen transfer and/or an increase in the biological activity, which led to a higher oxygen consumption. During these 22 months of monitoring, the performance in terms of organic matter removal was not very good, but still sufficient to allow compliance with local regulations (maximum COD of 180 $mg{\cdot}L^{-1}$ or minimum removal efficiency 55% – DN COPAM/CERH 01/2008). In terms of TSS and TKN, performance can be considered to be good, taking into account that the system comprised only two units in parallel. Among these parameters, the TSS showed significant difference when compared to the effluent concentration values of the two units, presenting better results in the unit with higher surface sludge accumulation. This condition is due to the better interception and filtration resulting from the lower porosity of this layer compared to the filtering material of the system, as highlighted by Molle (2014). As expected, due to the absence of specific mechanisms, total nitrogen removal was not high, but there was a substantial conversion to the oxidized form of nitrate as a result of nitrification.

Results from intensive monitoring over the feeding cycle

The values obtained from the characterization of the raw sewage (influent) and effluent from units I (with top sludge) and II (with sludge previously removed) over the seven days that comprised the feeding periods in the four monitoring campaigns are presented in Table SM1 (Supplementary Material). Below are presented and discussed the main results from the intensive monitoring campaigns.

Organic matter removal

The values of the influent concentrations in the intensive monitoring in terms of COD ranged from 158 $mg{\cdot}L^{-1}$ to 782 $mg{\cdot}L^{-1}$. Based on the median concentrations of 427 and 379 mg $COD{\cdot}L^{-1}$ and flow rate of 12.7 $m^3{\cdot}d^{-1}$, units I and II received, during feeding, a median surface organic loading rate of 184 g $COD{\cdot}m^{-2}{\cdot}d^{-1}$ (61% of the design load) and 164 g $COD{\cdot}m^{-2}{\cdot}d^{-1}$ (55% of the design load), respectively. The reference value for the design loading rate was 300 g $COD{\cdot}m^{-2}{\cdot}d^{-1}$, according to the recommendations of Molle *et al.* (2005).

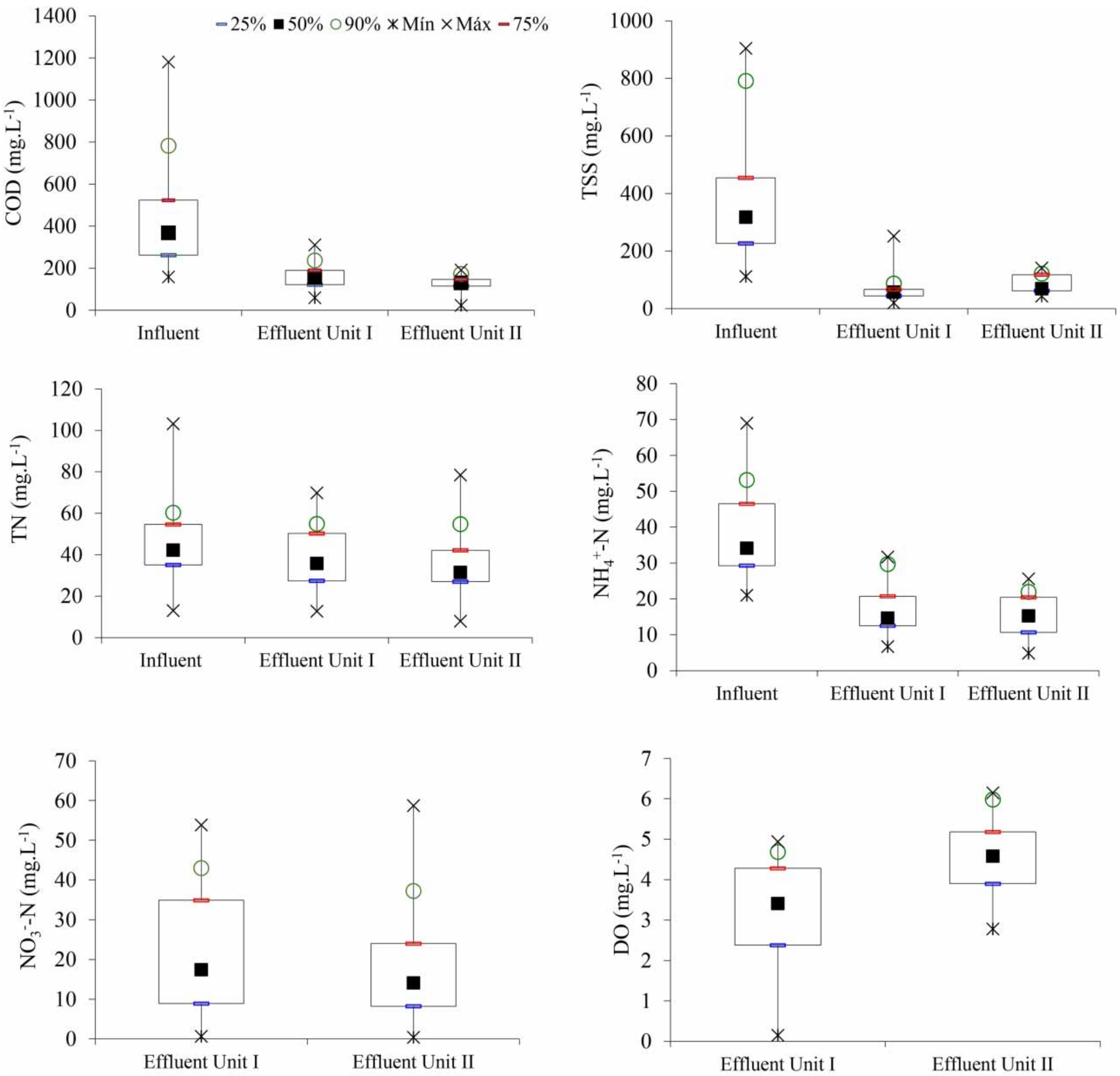

Figure 2 | Box-plots of influent and effluent concentrations from continuous monitoring: COD, TSS, TN, NH_4^+-N, NO_3^--N and DO. Unit I (with accumulated sludge) and unit II (with sludge previously removed).

Although in some feeding days during the intensive monitoring campaigns the applied load was above the recommendations from Molle *et al.* (2005), the removal efficiency in terms of COD concentration, day by day, was sufficient to comply with local regulations. The median effluent COD concentrations from both units (unit I: 147 mg·L^{-1} and 101 mg·L^{-1}, intensive campaigns Ia and Ib, respectively; unit II: 107 mg·L^{-1} and 82 mg·L^{-1}, campaigns IIa and IIb, respectively) were similar to those reported by Lombard Latune & Molle (2017). These researchers, investigating systems with two units in parallel (0.8 m^2 p.e.$^{-1}$), reported a sustained removal efficiency, as required in the legislation of the countries investigated. They obtained a consistent COD removal efficiency of 75% and an effluent concentration of 125 mg·L^{-1} (with a load of 284 g COD load m^{-2}·d^{-1}) in a system with 30 cm of total depth. They also obtained a removal efficiency of 90% and effluent concentration of 100 mg·L^{-1} (with 186 g COD load m^{-2}·d^{-1}) with 80 cm filter depth and intermediate drainage layer of 40 cm. Operated in tropical climate conditions, both systems alternated units with three and a half days of feeding and the same time for resting.

In the intensive monitoring campaigns, unit I obtained a slightly better removal efficiency in terms of COD than unit II (with sludge previously removed), with median values from the seven days of 71% and 68%, respectively. However, the differences were not statistically significant ($p = 0.561$). In the routine monitoring, the efficiency was 60% and

63%, respectively, for units I and II. The lower removal efficiency obtained in the conventional monitoring may be linked to factors such as dilution of the influent during rainfall events (intensive monitoring campaigns were all during dry weather), variable organic loadings that prevailed in the longer period of 22 months and lower heights of the sludge layer on the surface of the units. The median sludge accumulation rates in the studied units were 0.92 cm·year^{-1} in unit I and 0.42 cm·year^{-1} in unit II (Trein *et al.* 2018).

The COD concentrations in the effluent also varied over the feeding time. A higher concentration of COD in the effluent from day 0 was observed in all the campaigns (Figure 3). This was probably due to the release of solids and biofilms from the interior of the bed or the drainage pipe when the first pulse of the feeding period was applied. The peak concentration of COD (429 mg·L^{-1}) on the last day of monitoring IIa did not follow the other patterns, and one possible explanation for this event could be biofilm detachment caused by changes in the biomass characteristics along the feeding period. When interpreting the graphs, we should remember that, for the sake of simplicity, they display only effluent concentrations and removal efficiencies, which is sometimes insufficient to characterize the full dynamics taking place in the treatment units and in the influent loads.

As influent and effluent concentrations varied, COD removal efficiency varied on a daily basis during the feeding cycles. This may be related to the applied organic loading and the filtration potential of the units. Unit II presented greater variation of the results, justified by the lower solids retention and filtration capacity due to the smaller height of the deposit layer, also associated with a lower microbial activity in the shallower sludge layer. The effluent

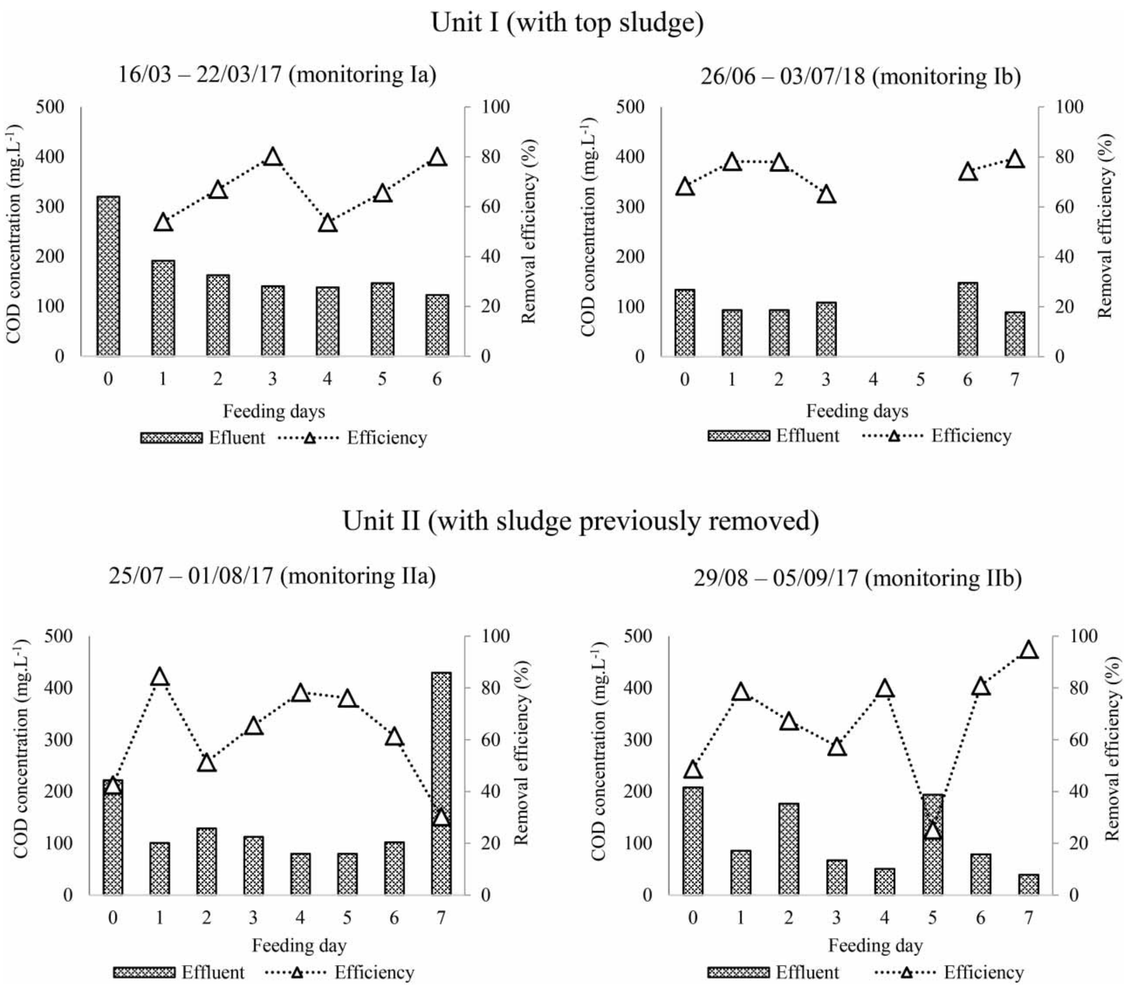

Figure 3 | Effluent COD concentrations (mg·L^{-1}) and COD removal efficiencies (%) over the seven days of the feeding cycle. Unit I (with top sludge) and unit II (with sludge previously removed).

concentration values from units I and II were in accordance with the treatment objectives of the first stage of the French system, demonstrating the adequacy of this system, even if operating with only two units.

Comparing the two monitoring strategies (intensive and conventional), it can be observed that the third day of conventional monitoring can represent the behaviour of the units in the seven days of the feeding cycle, excluding the first pulse (day 0) and the last feeding day of this extended feeding cycle of seven days. This was endorsed by results presented by Moraes *et al.* (2019), which indicated a different hydraulic behaviour in the first and seventh days of the feeding cycle in the same system.

Dissolved oxygen

As expected, as the liquid percolated downwards, the concentrations of effluent dissolved oxygen increased (Figure 4), considering that the raw sewage had typical null DO concentrations (data not presented). Throughout this extended seven day feeding period, the effluent DO concentrations were always positive, with median values of 3.0 and 3.6 mg $O_2 \cdot L^{-1}$ in the Ia and Ib campaigns, respectively, in unit I and 4.7 mg $O_2 \cdot L^{-1}$ in both campaigns in unit II. These values were similar to those obtained in the conventional monitoring (3.4 mg·L^{-1} and 4.6 mg·L^{-1}, respectively, in unit I and unit II).

The transfer of oxygen to the bed may have been achieved by convection due to pulse loading, diffusion and passive aeration (Platzer 1999; Molle *et al.* 2006). Since both units worked with the same operating conditions (number of pulses, HLR, instantaneous hydraulic loading rate – HLR_{inst}, pulse time) and no rainfall was recorded during the monitoring campaigns, the lower DO concentrations measured in unit I (with significant difference $p < 0.005$) were likely to have been mainly influenced by the greater accumulation of deposits on the surface of the filter bed (average height of 7.2 cm), compared to unit II (average sludge height of only 0.5 cm at the end of all the campaigns) (results presented in Trein *et al.* 2018) – see Figure SM1 in the Supplementary Material.

According to Molle *et al.* (2006) and Molle (2014), the higher the height of the sludge layer, the greater the amount of immobilized water, which, in turn, influences the infiltration rate and the oxygen renewal into the filter mass. In this way, Molle (2014) emphasizes that hydraulic and organic loads must be well controlled in order to favour the mineralization of the deposit layer, otherwise limited oxygen transfer (convection and diffusion) may take place due to excess surface water, influencing the performance of the system in the units of the present research. Garcia Zumalacarregui (2018) demonstrated by gas tracer (propane) tests that the oxygen transfer rate in unit I was 194 g $O_2 \cdot d^{-1}$ and in unit II was 230 g $O_2 \cdot d^{-1}$, suggesting a negative influence of accumulation of sludge on the surface layer. In addition to the sludge layer, Garcia Zumalacarregui (2018) pointed out that the elevated position of the distribution pipe (0.25 m above the surface of the filter medium) played an important role in the increase of the oxygen transfer due to gravity aeration.

In general, the extended feeding regime of seven days was associated with a decrease in the oxygen concentration with the passage of time. For all the monitoring campaigns performed, the concentration decreased substantially from the fourth to the seventh day of feeding. It is important to note that, on the last day of feeding, the upper layer of the filter showed signs of surface hydraulic saturation. This condition may hinder the transfer of oxygen to the bed and the removal of pollutants. The lower DO concentrations in the effluent from unit I may also be related to the greater

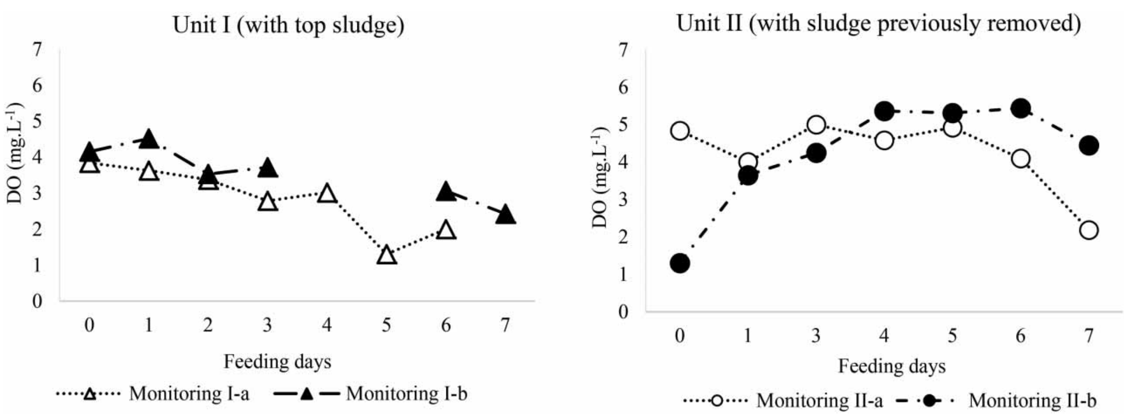

Figure 4 | Behaviour of dissolved oxygen concentration in the effluent from units I and II over the seven-day feeding cycle.

development and metabolism of the bacteria oxidizing the organic matter present in the sludge.

In a study carried out in the same treatment plant, after two years of operation, mean concentrations of 5.1 mg $O_2 \cdot L^{-1}$ in the effluent were identified, but the operating strategy was different, with two and a half days of feeding and four and a half days of resting, using three units in operation (Lana *et al.* 2013). It is noteworthy that with the passage of time (seven years of operation), the oxygen transfer conditions in the filter bed may have been affected, mainly influenced by the greater accumulation of solids in the upper part of the filter, the feeding of each unit lasting a longer period of time (seven days, as opposed to the previous two and a half days) and the utilization of only two units (as opposed to the prior use of three units in parallel). However, even with these modifications, effluent DO concentrations remained high throughout.

Nitrogen transformations

In terms of nitrogen removal, it is expected that the utilization of only the first stage of the French system presents limitations for achieving full nitrification, with efficiencies of nitrification expected to be around 50%, for applied loads ranging from 25 to 30 g $TKN \cdot m^{-2} \cdot d^{-1}$ (Molle *et al.* 2005). Several factors may be influential, such as operational conditions (alternating filters, feeding strategies, applied hydraulic and mass loads), oxygen transfer rate to the interior of the filter bed, composition of the influent wastewater, design considerations (filter height, characteristics of the filter material) or external parameters (maintenance level, climatic conditions) (Boller *et al.* 1993; Molle *et al.* 2006; Torrens *et al.* 2009; Molle 2014; Millot *et al.* 2016; Nakamura *et al.* 2016).

In the system studied, the removal of TKN, as well as the production of oxidized nitrogen ($NO_x = NO_3^-$-N + NO_2^--N), varied over the seven days of the feeding period in all campaigns, as shown in Figure 5.

With applied loads within the ranges recommended in the literature, the median removal efficiencies of TKN in the two intensive campaigns done in each unit were 67% and 58% for unit I and 46% and 63% for unit II. In all campaigns the nitrification rate varied, with a tendency to increase the concentrations of effluent NH_4^+-N and decrease NO_3^--N concentrations along the feeding cycle. Possible factors that could explain this could be that the NH_4^+-N adsorbed is nitrified between the feeding and resting periods, being then released with the first pulse of the new cycle, as reported by Boutin *et al.* (1997) and Paing *et al.* (2015). As a result, after the resting period of one week, without receiving raw sewage, the concentrations of NO_3^--N are high. Based on modelling of the amount of nitrogen previously adsorbed in the VCW-FS, Morvannou (2012) reported a reduction of 84% of NH_4^+-N during the resting period, and a measured increase of 62.4% in NO_3^--N concentrations in the effluent in the subsequent cycle. These observations explain and confirm the substantial nitrate flux generally measured in the VCW effluent during the first pulse (Molle *et al.* 2006). Another possible explanation is the occurrence of higher aerobic conditions inside the filter at the beginning of the feeding period, which would not limit nitrification. As the feeding time progresses, there is a greater accumulation of liquid in the upper layer, making drainage and the potential of oxygen diffusion more difficult.

The NH_4^+-N conversion over the feeding cycle differs from the results obtained by Arias Lopez (2013), who studied the behaviour of a VCW-FS receiving feeding for 11.5 days, with an applied surface hydraulic loading rate of 0.38 $m^3 \cdot h^{-1}$. The author reported a progressive efficiency of ammonium conversion, starting with 65% on the first day, reaching 80% at the end of the cycle. Arias Lopez (2013) stated that this condition was dependent on the resting period that preceded the first days of feeding, which was responsible for the lower activity of the nitrifying bacteria at the beginning of the cycle. Besides that, the author emphasized the improved distribution of the raw sewage on the surface of the system with the formation of a thicker sludge layer with more feeding days, occupying a larger reactive volume of the reactor (Arias Lopez 2013).

The resting period is an energy deficiency condition for the bacteria, which then need to rebuild their nutritional reserves during the feeding period (Boutin *et al.* 1997). According to Silveira (2015), investigating a different system, during the seven resting days, when the unit received no additions, the quantity of microorganisms of different species responsible for the treatment progressively decreased, and later on increased with more feeding days. According to the author, this resting period was recommended as sufficient to prevent an excessive decay of the bacterial community in VCW-FS under the French climatic conditions.

In addition to better operational flexibility, longer feeding periods (seven days) may provide better survival conditions for specific organisms during the resting period of the units, due to the higher water retention capacity in the system caused by biofilm growth and the formation of a further layer of sludge on the surface of the system. For

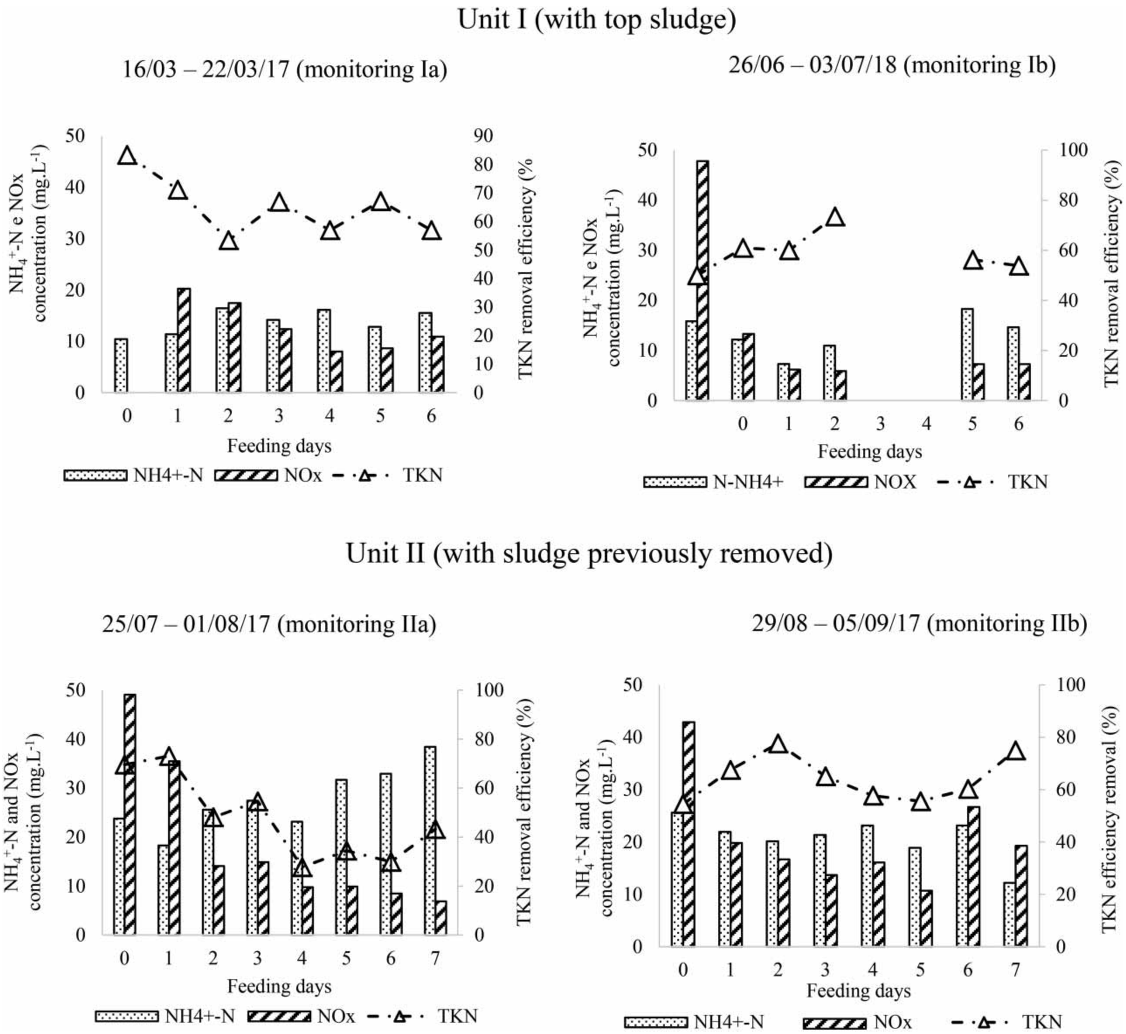

Figure 5 | Behaviour of the nitrogen series in the effluent from units I (with top sludge) and II (with sludge previously removed) during the intensive monitoring campaigns.

the operational conditions of this research, the recovery of the liquid applied in the units was not complete between one pulse and another (Moraes *et al.* 2019). It was observed that the liquid that was retained inside the system was released in the resting period. The adsorption capacity of the filter bed and deposit layer has a 'spongy effect' (Chazarenc & Merlin 2005) that allows the release of water during the resting period (Prigent *et al.* 2013), keeping the microbial community active during this period (Molle *et al.* 2015).

Based on TKN concentrations, the removal efficiency in the intensive monitoring in unit I was 62% and in unit II 64%. These efficiencies can be considered to be good, given the reduced area of this system. These performance values are close to those observed in a temperate climate (Molle *et al.* 2008). Morvannou *et al.* (2015) describe removal efficiencies of 59% and Molle *et al.* (2005) of 58% and 60%.

Similar to what was observed by Paing *et al.* (2015), TKN was not impacted by the increase in organic load. The highest TKN removal efficiencies reported in unit II (73% and 75% for campaigns IIa and IIb, respectively) occurred during the highest loads (283 and 338 g COD$\cdot$m$^{-2}\cdot$d^{-1} respectively) and 67% for loadings greater than 300 g COD$\cdot$m$^{-2}\cdot$d^{-1} (design recommendations by Molle *et al.* 2005) in unit I.

The potential to promote nitrification is associated with the operation and physical structure of the treatment systems, which provide sufficient retention time to allow contact with the bacteria that are responsible for the oxidation of NH_4^+-N (Kantawanichkul *et al.* 2009). Therefore, the contact and resting periods should be optimized according to adsorption and nitrification kinetics, respectively. In VCW, direct nitrification seems to be limited by the ammonia retention time in the media caused by the rapid flow velocity, limiting the adsorption of ammonia on the biofilm, organic matter and soil minerals (Molle *et al.* 2006, 2008; Hu *et al.* 2014). In the units of the present study, the effluent flow peak occurred within 10 minutes of the liquid application on the surface of the units. The difference in liquid percolation time was greater in the unit with sludge, indicating a positive effect in terms of increased biodegradation time, but also a greater difficulty of infiltration compared to the unit with lower sludge accumulation (Moraes *et al.* 2019).

Comparing the results of the two units, no significant difference was observed in terms of removal efficiency for TKN and NH_4^+-N ($p = 0.417$ and 0.272). The absence of sludge did not influence the good performance in terms of nitrate production expected for the first stage, which, according to Molle *et al.* (2006), can be influenced mainly by the operating conditions (pulse frequency, instantaneous loading rates, intervals between feeding and resting).

In Figure 2 (conventional monitoring over 22 months), the nitrogen graphs show similar median values to those from the intensive monitoring. However, attention should be drawn to the variation in influent TKN data and NO_3^--N production in both units. These variations can be explained by various reasons, such as mass and hydraulic loading, external influence such as Tifton 85 grass growth stage, precipitation and temperature. It is important to highlight that the values presented in this paper were not separated according to the different seasons, a condition reported by Pálfy *et al.* (2017) as influencing the nitrification rate. According to these authors, the potential for adsorption and regeneration of the medium was higher in summer, indicating different resting times over the year, being half a week in summer, one week in spring and at least two weeks in winter. However, it should be noted that seasonal variations under tropical conditions, such as in the current research, are much less pronounced than in temperate climates.

The data of the effluent concentrations and removal efficiencies in terms of NH_4^+-N and TKN during the days of the feeding cycle, as obtained in the intensive monitoring campaigns, may be useful to assess the dynamics of nitrogen along the feeding period. Therefore, in-depth studies on the behaviour of the nitrogen forms (NH_4^+-N, NO_x) requires intensive monitoring over the feeding cycle.

CONCLUSIONS

This study analysed the operation and discussed the behaviour, limitations and applicability of an extended feeding of seven days (instead of three and a half days, usually recommended in France) in a VCW-FS comprised only of the first stage, which operated with only two units in parallel. Some important conclusions derived from the study are presented below.

An extended feeding period may be acceptable in systems installed in tropical climate regions. This condition reduced operational requirements, but had implications in terms of performance in the last days of the feeding period.

The removal of organic matter (COD) over the seven days that composed the feeding cycle was within what could be expected for the first stage of VCW-SF operating with a reduced area.

The NH_4^+-N concentrations varied over the feeding days. In all intensive monitoring campaigns, NO_3^--N production in both units was higher in the first pulse, progressively decreasing as the feeding period progressed, coinciding with the unit's effluent oxygen concentration.

For conventional routine monitoring campaigns based on weekly samplings, monitoring on the third day of the feeding cycle, at its mid-point, seemed to be a good representation of the main typical conditions prevailing over the days of an extended feeding cycle of seven days. However, this statement is confined to the system under study, and also to the limited number of intensive campaigns carried out.

Based on the intensive monitoring, it was observed that the system performance was as expected, starting with acceptable COD removal efficiencies, high effluent oxygen and NO_3^--N concentrations, good NH_4^+-N removal efficiency, and ending the cycle with medium saturation conditions and a decrease in the efficiency of conversion associated with oxidative processes.

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SUPPLEMENTARY MATERIAL

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