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Case Report

Recycled Shredded-Tire Chips Used As Support Material in a Constructed Wetland Treating High-Strength Wastewater from a Bakery: Case Study

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Abstract: Support material used in constructed wetlands has been shown to be a key element and significant mechanism in the process of contaminants removal from sewage including phosphorus compounds. Recycled waste tires processed into small chips that are similar to conventional stone aggregate are currently used in the construction of septic system leach fields and could be a green alternative as support material in constructed wetlands. During three years, the performance of a gravity subsurface horizontal flow constructed wetland using recycled shredded-tire chips as support material to treat on-site the high strength wastewater from a bakery was monitored. Grab samples of the effluent from the septic tank and the constructed wetland were collected quarterly and submitted to a certified laboratory. Final treatment efficiency (percentage removal) was low for potassium (36%), intermediate for total nitrogen (56%), and total Kjeldahl nitrogen (57%), and relatively high for total phosphorus (65%), total suspended solids (69%), ammonia-nitrogen (87%), five-day biochemical oxygen demand (92%), *Escherichia coli* (97%), and fat-oil and grease total (99%). Nitrate-nitrogen final mean value was consistently below 1 mg/L, and iron concentration increased from less of 2 mg/L in the sewage to 55 mg/L in the constructed wetland effluent. These results show that recycled shredded-tire chips could be an environmental alternative support material in constructed wetlands as efficient removal of typical wastewater contaminants is not compromised.

Keywords: constructed wetland; high-strength sewage; recycled tires; shredded-tire chips

1. Introduction

The support material used in constructed wetlands (CWs) has been shown to be a key element and significant mechanism in the process of pollutants removal from wastewater. Research has been done testing sewage treatment efficiency of CWs using different support materials, such as gravel [1,2], shale, ironstone and hornblende [3] combination of sand and dolomite [4], and volcanic gravel rock [5].

Recycled waste tires processed into small chips are used as a filter media in the construction of septic systems absorption or leach fields [6]. The recycled shredded-tire chips material is coarse aggregate, lightweight material with long term stability and maximum storage capacity: tire chips have a porosity of 0.6, and the gravel has a porosity of 0.4 [7]. The bulky characteristic of tire chips saves in the support material as less material is required to cover same space [8]. Additionally, tire chips have good ion-exchange capacity, which allows them to work as buffer material adsorbing and releasing NO^{-}_{3}-N [9]. Those properties can be useful for wastewater treatment as tire rubber can retain no only NO^{-}_{3}-N but phosphorus compounds reducing their leachate to the soil and eventually to the ground or surface waters, however; the mechanism of how the mitigation works remains unclear [10]. Recycled shredded-tire chips could be an environmental alternative to river stone or other local media as support material in constructed wetlands. This three-year case study reports the performance of a subsurface gravity horizontal flow constructed wetland (GHFCW) using recycled shredded-tire chips as support material to treat on-site high-strength wastewater from a bakery.

2. Materials and Methods

A GHFCW cell (12 m × 6 m; 0.6 m deep) to treat on-site high-strength sewage from a bakery was built in LaGrange County, Northeast Indiana. Volume of sewage to be treated was assumed as approximately 2124 L per day according to the current commercial regulations from the Indiana State Department of Health for the proposed type of business. The 6-day per week, and 16-h bakery operation also included a public cafeteria serving coffee and ready to eat food dishes.

The wastewater from the kitchen and the bakery operation was collected in a 4732-liter septic tank working as a grease trap. Effluent leaving the grease trap runs by gravity to the front end section of a second 4732-liter septic tank, which it was also receiving sewage generated from the public and employees restrooms (Figure 1). The high strength effluent passed through a plastic filter located at the outlet of the second septic tank, and gradually released by gravity to the feeding inlet bottom of the wetland cell, which used plastic chambers to spread the incoming sewage at the front end. The GHFCW cell was built with a 0.0762 cm PVC liner and filled with a bottom layer of 45 cm depth of 40–80 mm diameter recycled shredded-tire chips, and a top layer of 15 cm depth of 4 mm diameter gravel (pea gravel) (Figures 2 and 3). The top of the wetland cell was planted with four transplanted wildlife cattails on the corners and a dozen of water irises planted on the center of the wetland cell to enhance the system landscaping (Figure 4).

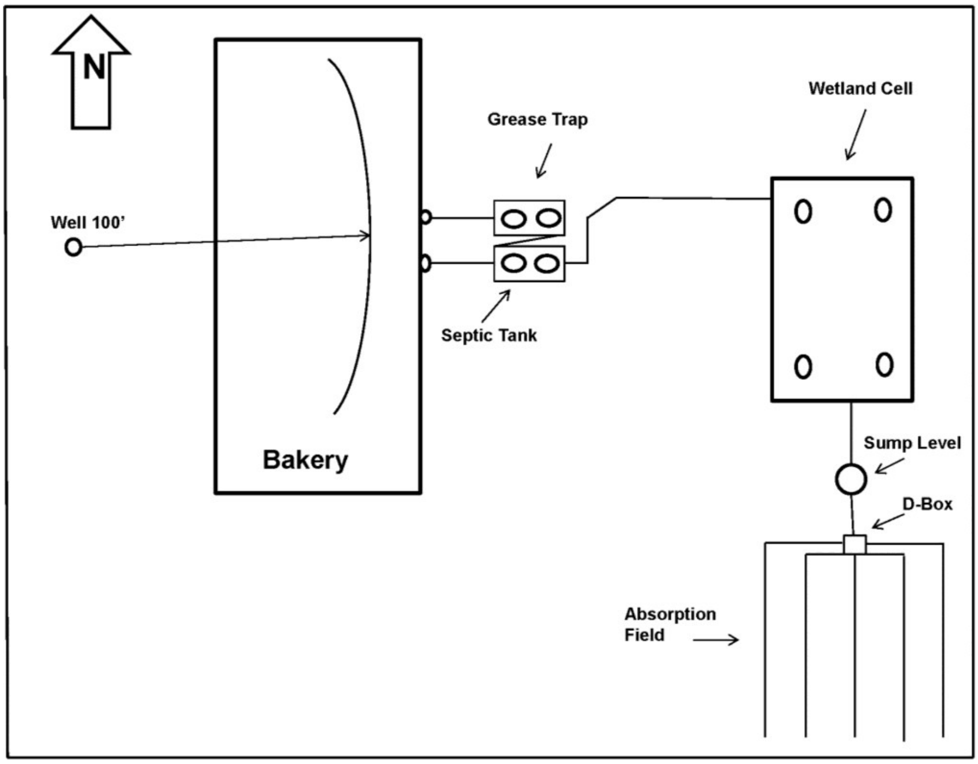

Figure 1. Site plan with components of the on-site wastewater system.

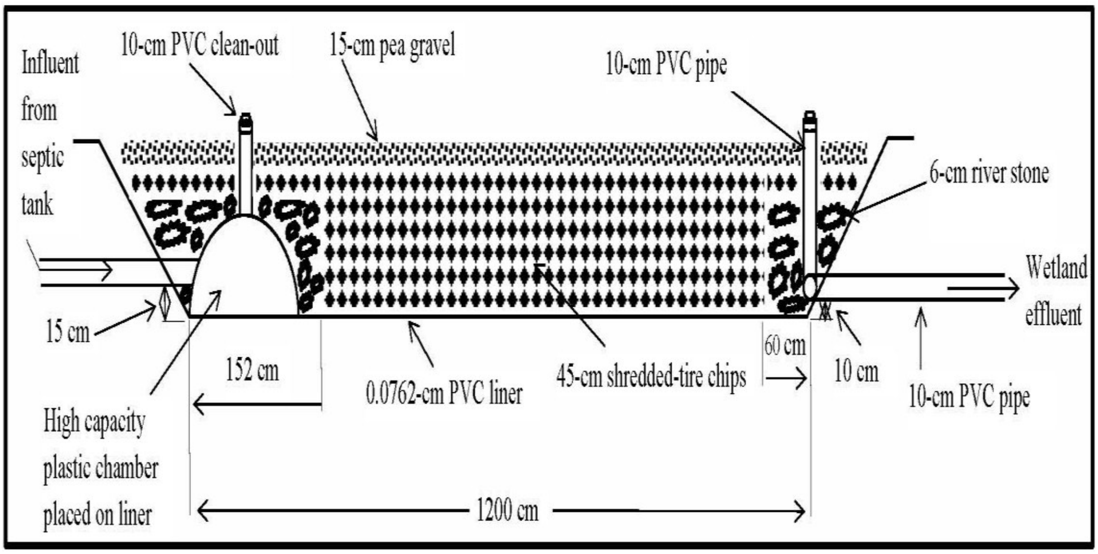

Figure 2. Longitudinal view of the horizontal flow constructed wetland.

Figure 3. Front view of the constructed wetland cell showing the shredded-tire chips.

Figure 4. Aspect of the constructed wetland after the first year of installed.

During three years; grab samples of the effluent from the septic tank and the constructed wetland were collected quarterly, and transported in refrigerated coolers (4 °C) to a certified Environmental Protection Agency (EPA) testing laboratory. The samples were analyzed immediately after arriving to the laboratory using the methodology described in Standard Methods (SM) for the Examination of Water and Wastewater [11], and in the EPA Manual of Methods for Chemical Analysis of Water and Wastes [12] for the following parameters including the analytical reporting detection limit for each test: 5-day biochemical oxygen demand (BOD_5, SM-5210-B, 2 mg/L), nitrate-nitrogen (NN) (NO^{-}_3-N, EPA-353.2, 0.1 mg/L), ammonia-nitrogen (AN) (NH_4^+-N, SM-4500-NH_3-D, 0.1 mg/L), total suspended solids (TSS, SM-2540-D, 3 mg/L), fecal coliforms bacteria (EC) (*Escherichia coli*, SM-Quanti-Tray/2000, 1 MPN/100 mL), total phosphorus (TP, SM-4500-P, 0.1 mg/L), potassium (K, EPA-200.7, 2 mg/L), iron (Fe, EPA-200.7, 0.2 mg/L), fats, oil and grease, total (FOG, HEM-EPA-1664, 5 mg/L), and total Kjeldahl nitrogen (TKN, EPA-351.2, 2 mg/L). Parameters collected on-site at the constructed wetland outlet sump pit, and the septic tank included temperature (air and water), dissolved oxygen, oxygen reduction potential, and pH. The removal efficiency was calculated according to the equation used by Ebeling *et al.* [13].

3. Results and Discussion

The wastewater treatment system was designed to treat a daily sewage flow of 2124 L; however, a water well meter to check water consumption did show a daily real flow (mean ± standard deviation) of 4191 ± 1120 L considering only six days per week for scheduled business operations. There is a percentage of the water added to prepare the dough that is evaporated during the baking process and it is not ending as wastewater. The bakery's owners indicated that 25% of the daily water flow should be ending as final baked products. Under this consideration the amount of daily sewage (3143 liters) generated by the bakery was one and half times the daily flow capacity of the CWs wastewater treatment system. The theoretical hydraulic retention time (HRT) of the sewage inside the septic tanks (9464 L) divided by the influent flowrate (3143 L/day) was ±72 h. Assuming the same flowrate passed directly to the GHFCW, the HRT of the septic tank effluent inside the wetland cell was ±4 days. A field test to determine a more accurate HRT was not performed. Over time, plants and accumulated sludge can negatively change the HRT. As a technical note, the support material was not changed during the testing period. The wastewater treatment system was always operational as required and clogging issues were not visible during the three-year testing period. Additionally, decaying death material was not allowed to accumulate on top of the pea gravel. Every spring a complete cleanup of the dead material was performed to allowing the new vegetative material to grow.

Results of influent (septic tank sewage) *vs.* effluent from the CWs, and treatment efficiency for DO, ORP, pH, air and water temperature, BOD_5, TSS, TP, K, coliform bacteria (Table 1), and nitrogenous compounds (Table 2) fluctuated during the three-year testing period. The capacity of the GHFCW to remove contaminants fluctuated from a low 36% (K) to high up to 99% for FOG (Table 3).

According to Benefield [14] the following range values could be used to define sewage as high-strength: BOD_5 (100–3685 mg/L), TSS (142–4375 mg/L), and FOG (25–14958 mg/L). Per data from Table 1 and Table 3, the constructed wetland septic system serving the bakery received wastewater that can be classified as high-strength sewage using Benefield [14] definition. Bakeries are a type of business that usually generates larger amounts of wastewater containing high amounts of FOG. High values for FOG also increases the concentration of BOD_5.

The constructed wetland used in this case study was able to reduce the inlet concentration of FOG from 1102 to 5 mg/L in the outlet showing removal efficiency over 99%. Additionally, there was a high removal efficiency for BOD_5 (92%) dropping from 2373 mg/L in the influent to 197 mg/L as effluent treated. For BOD_5, the removal efficiency of the constructed wetland system used in this case study showed better or similar performance than values reported by other researches using support material different than shredded-tire chips. Zurita, F. *et al.* [15] using local gravel rich in iron oxide (volcanic rock) as support material reported BOD_5 removal efficiency fluctuating between 74% and 78% for a horizontal flow constructed wetland treating domestic wastewater in lab-scale and pilot-scale studies. The study by [16] reported high BOD_5 removal efficiencies (96%) using stone as substrate in a subsurface constructed wetland; however, the constructed wetland was fed with pretreated raw wastewater passed first through an upflow anaerobic sludge blanket.

Table 1. Mean concentration and standard deviation (SD) for dissolved oxygen (DO), temperature (°C), 5-day biochemical oxygen demand (BOD_5), total suspended solids (TSS), total phosphorus (TP), and fecal coliforms bacteria (*E. coli*). MPN: most probably number.

Age	DO (mg/L)		T (°C)		BOD_5 (mg/L)		TSS (mg/L)		TP (mg/L)		*E. coli* (MPN)	
(Days)	In	Out	In	Out	In	Out	In	Out	In	Out	In	Out
30	1.2	1.5	23.5	17.7	850	20	170	10	4.92	0.85	9×10^4	3×10^4
83	1.94	1.6	22.9	21.5	830	150	330	85	8.22	0.55	17×10^4	12×10^4
101	0.02	0.04	26.6	22.9	710	510	240	220	7.24	1.3	98×10^3	12×10^3
148	0.22	0.26	25.1	16.3	2200	96	351	90	4.89	2	33×10^5	25×10^3
188	0.07	0.25	24.5	15.3	1400	120	160	130	1.7	0.41	39×10^5	3×10^3
318	0.33	0.21	22.6	11.1	2000	560	240	140	2.33	0.76	9×10^3	7×10^3
370	1.5	1.3	19.1	5.3	3100	160	360	150	6.54	0.363	9×10^2	5×10^2
436	2.2	4.6	20.9	17.3	1800	610	210	270	6.6	2.12	1×10^5	4×10^4
510	3.2	3.5	28.0	25.7	4200	99	1100	140	4.48	1.72	9×10^3	5×10^3
655	1.4	1.3	23.2	19.8	1900	110	310	150	7.28	4.53	9×10^4	4×10^4
775	1.3	1.4	24.5	21.6	1600	18	276	74	6.76	5.47	9×10^3	2×10^3
895	1.51	2.1	17.8	5.6	5680	186	464	80	3.76	1.95	2×10^4	2×10^4
1015	2.2	1.3	25.9	23.2	3790	31	592	62	4.5	1.6	1×10^6	2×10^3
1115	1.9	1.1	26.3	20.5	3160	87	552	38	3.6	2.2	2×10^5	1×10^4
Mean	1.4	1.5	23.6	17.4	2373	197	383	117	5.2	1.8	8×10^5	2×10^4
SD	0.9	1.3	2.9	6.3	1445	610	245	69	1.9	1.5	13×10^5	3×10^4

Table 2. Mean concentration, and standard deviation (SD) for ammonia-nitrogen (NH^+_4-N), nitrate-nitrogen (NN = NO^-_3-N), total-Kjeldahl-nitrogen (TKN), and total-nitrogen (TN = TKN + NN).

Age	NH^+_4-N (mg/L)		NO^-_3-N (mg/L)		TKN (mg/L)		TN (mg/L)	
(Days)	In	Out	In	Out	In	Out	In	Out
30	14.8	3.62	0	0	33.5	14.1	33.5	14.1
83	25.1	13.3	0	0	119	56.6	119	56.6
101	31.6	0.19	0	0	63.4	23.4	63.4	23.4
148	39.3	4.42	0	0	127	20	127	20
188	35.2	0.2	0	0	40.2	14.7	40.2	14.7
318	38.8	0.16	0	0	33.7	25.8	33.7	25.8
370	23.4	0.126	0	0	53.2	27.7	53.2	27.7
436	41.4	2.12	0	0	39.3	21.6	39.3	21.6
510	47.6	4.01	0.5	0.5	47	4.1	47.5	4.6
655	36.7	11.4	0.5	0.5	57.3	37.2	57.8	37.7
775	14	7.7	0.5	0.7	60.2	39.3	60.7	40
895	12.8	0.05	0.5	0.5	54	31.3	54.5	31.8
1015	24.5	0.35	0.5	0	44.8	20.5	45.3	21
1115	16.9	3.4	0.8	0.5	30	12.9	30.8	13.4
Mean	28.7	3.6	0.24	0.19	57.3	24.9	57.5	25.09
SD	11.8	4.4	0.29	0.27	29.7	13.2	29.6	10.9

Table 3. Treatment efficiency of the horizontal flow constructed wetland. MPN: Most Probably Number, NA: not applicable. Mean concentration (standard deviation = SD).

Water Quality Parameters	**Subsurface Horizontal Flow Constructed Wetland {Mean (SD)}**		
	Influent	**Effluent**	**Efficiency (%)**
Fat, Oil and Grease {FOG (mg/L)}	1101 (150)	5.3 (0.5)	99
Fecal Coliforms {*E. coli* (MPN/100 mL)}	8×10^5 (13×10^5)	2×10^4 (3×10^4)	97
Biochemical Oxygen Demand {BOD_5 (mg/L)}	2373 (1445)	197 (610)	92
Ammonia-N {NH^+_4-N (mg/L)}	28.7 (11.8)	3.6 (4.4)	87
Total Suspended Solids {TSS (mg/L)}	383 (245)	117 (69)	69
Total Phosphorus {TP (mg/L)}	5.2 (1.9)	1.8 (1.5)	65
Total Kjeldahl Nitrogen {TKN (mg/L)}	57.3 (29.7)	24.9 (13.2)	57
Total-Nitrogen {(TN = TKN + NN) (mg/L)}	57.5 (29.6)	25.09 (10.9)	56
Potassium {K (mg/L)}	31.9 (8.9)	20.5 (9)	36
Nitrate-Nitrogen {NN = NO^-_3-N (mg/L)}	0.24 (0.29)	0.19 (0.27)	NA
Dissolved Oxygen {DO (mg/L)}	1.4 (0.9)	1.5 (1.3)	NA
pH (standard units)	3.9–6.2	6.3–7.6	NA
Water Temperature (°C)	23.6 (2.9)	17.4 (6.3)	NA

The average removal for TSS during the experimental period was reduced from 383 mg/L in the inlet to 117 mg/L at the outlet showing an efficiency removal of 69%. Zurita, F. *et al*. [5] reported TSS removal up to 82% by a horizontal flow constructed wetland (HFCW) treating influent similar to typical sewage from household. A HFCW treating fermented fish production wastewater reached 88% removal of solids [16]. The lower value of solids removal by the constructed wetland used in this case study in comparison with other reports could be related to the higher daily water uses, which was over one and half times the treatment capacity for which the system was designed. This situation could have increased the velocity of the sewage passing through the wetland cell, reducing the time for sedimentation and filtration; the two main processes responsible for solid removal in constructed wetlands.

Nitrification process was efficient dropping AN from 29 to 4 mg/L (87%), TKN from 57 to 25 mg/L (57%), and TN was reduced from 58 to 25 mg/L (56%). The final NN was consistently below 1 mg/L. Values in this study were better than to those by [16]. They reported a reduction of 53% and 70%, for TKN and AN, respectively; and NN fluctuated from 0.17 to 3.4 mg/L. Their system treated wastewater from a fermented fish production; however the wastewater passed first through an upflow anaerobic sludge blanket. The constructed wetland system used in this case study shows low efficiency removal for TN (59%) in comparison with the research done by [17] using a laboratory-scale constructed wetland treating residential sewage. They reported TN removal up to 87% as a result of effective high oxygenation of the system as dissolved oxygen concentration ranged from 5.2 to 7.4 mg/L. The constructed wetland system in this case study had a final oxygen concentration of 1.5 mg/L; with a range from 0.2 to 4.6 mg/L. Additionally, another factor to be considered affecting low TN removal could be the pH concentration of the sewage entering the constructed wetland. Ammonification to convert organic-N back into ammonium is pH dependent with an optimum range from 6.5 to 8.5 standard units (SU). The final average value for the septic tank effluents (GHFCW influent) was 5.1 SU (lowest value was 3.9 and the higher value was 6.2); which is a value located more toward the acid side of the pH scale.

Phosphorus is considered a nuisance and its presence on surface water can allow an excessive grown of algae that consume the oxygen, forming eutrophic ecosystems. The GHFCW used in this case study reached 65% removal efficiency reducing TP concentration from 5.2 mg/L in the inlet to 1.8 mg/L at the outlet. According to [18], constructed wetlands do not remove significant quantities of phosphorus, except if special media with high phosphorus adsorption capacity is used but this could generate an additional cost if it is not locally available. Typically, horizontal flow constructed wetlands remove 40% to 60% of phosphorus [19]. In addition, the support material used in CWs has been shown as a key element to phosphorus removal, and it has been compared in different studies. Gravel did show the lowest phosphorus removal efficiency (21%) followed by ironstone and hornblende both with a 33% efficiency [3]. A mixture of sand and dolomite reached a removal efficiency of 45% for phosphates [4]. A constructed wetland equipped with a calcite filter showed 62% phosphorus removal efficiency. The removal in the calcite filter was initially good, but after three months all P-filters were saturated [20]. Garcia-Perez, A. *et al.* [21] reported 76% for phosphorus removal using gravel as substrate, however they used a recirculating vertical flow constructed wetland growing and harvesting corn, a crop commodity that specifically uses large amount of phosphorus during the growing season. Iron-rich volcanic rock used as support material reached 81% phosphorus removal [17]. The high efficiency to removing phosphorus (65%) reached by the GHFCW used in this case study can be explained by the presence of metals, specifically the iron from the exposed wires of the tire chips. Any phosphorus present in the sewage could have reacted with the iron creating insoluble phosphorus compounds. The precipitation and sequestration of those phosphorus compounds within CWs using support media rich in iron has also being reported by others researchers [22–24].

During this study, the iron concentration increased from the normal 2 mg/L in the septic tank to 55 mg/L at the GHFCW effluent. Concentration of iron up to 22.6 mg/L from water collected within monitoring wells installed around septic leach fields using tire chips as media has been reported [6]. Wires of the recycled shredded-tire chips can be considered a good source for iron as a typical passenger tire is composed approximately of 10 to 15 percent of ferric material [24]. Potassium was measured considering the potential negative effect of high salt concentration on soil. Studies showing the efficiency of constructed wetlands to remove potassium from wastewater are limited. Thus, this datum (36% removal efficiency) is significant to show that constructed wetlands can also remove potassium. The concentration of potassium in effluents from domestic wastewater sources ranges from 18 to 57 mg/L [25].

4. Conclusions

The three-year case study monitoring the discharged effluent from the constructed wetland suggests that using recycled shredded-tire chips as support material performed well. The efficiency removal after three-year operation was high for TOG (99%), EC (97%), BOD_5 (92%), AN (87%), and TSS (69%). Nitrate-N final mean value was consistently below 1 mg/L. Iron concentration increased, and removal efficiency for phosphorus reached 65%. For this specific case study, a continue good performing and life expectancy of the CWs as a functional sewage treatment system is unknown considering the daily volume (>2124 LPD) of high-strength wastewater passing through the wetland cell. Also, this GHFCW was not designed to treat this type of sewage. It was only used to test the performance of recycled shredded-tire chips as support material to treat sewage. These results indicated that recycled shredded-tire chips could be an environmental local alternative to river stone or other local material as support material in constructed wetlands. The efficiency to removing typical wastewater contaminants is not compromised. Similar to any new testing technology, early applications of recycled shredded-tire chips in constructed wetlands will serve as the initial baseline point for improvement, refining and developing better future generations of the proposed system to treat sewage onsite.

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Author Contributions

Alfredo García-Pérez, Mark Harrison, Craig Chivers and Bill Grant contributed to the design of the case study, analysis, interpretation of the results, and/or preparation of the manuscript. Additional contributions included the water sampling and data collection from the field, which they were performed by Alfredo García-Pérez, and Craig Chivers. Mark Harrison, Craig Chivers and Bill Grant provided additional reviews and proof reading for any changes regarding comments and/or reviews. Alfredo García-Pérez was the corresponding author keeping co-authors informed about the reviews and comments from the referees and the editorial office, plus updating the manuscript as required.

Conflicts of Interest

The authors declare no conflict of interest.

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