J Appl Phycol (2016) 28:629–642
DOI 10.1007/s10811-015-0544-2

Seaweed compost for agricultural crop production

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Received: 16 November 2014 / Revised and accepted: 5 February 2015 / Published online: 24 March 2015

Abstract This study manipulated the carbon-to-nitrogen ratio (C:N) of seaweed composts by varying the proportion of high N green seaweed (*Ulva ohnoi*) and high C sugarcane bagasse to assess their quality and suitability for use in agricultural crop production. Seaweed-bagasse mixes that had an initial C:N ratio greater than 18:1 (up to 50:1) could be transformed into a mature compost within 16 weeks. However, only composts with a high seaweed content and therefore low initial C:N (18 and 22:1) supported a consistently high rate of plant growth, even at low application rates. Sugarcane grown in these high seaweed composts had a 7-fold higher total above-ground biomass than low seaweed composts and a 4-fold higher total above-ground biomass than sugarcane grown in commercial compost that did not contain seaweed. Overall, the optimal initial C:N ratio for seaweed-based compost was 22:1 which corresponds to 82 % seaweed on a fresh weight basis. This ratio will produce a high quality mature compost whilst also ensuring that a high proportion of the nitrogen (>90 %) in the *Ulva* biomass is retained through the composting process.

Keywords Macroalgae · Phosphorous · Nitrogen · Agriculture · Salt · Electrical conductivity

Introduction

Land-based aquaculture is an important component of the global production of seafood with more than 65 million tonnes of fish, crustaceans and molluscs cultivated annually in land-based systems (FAO 2014). The intensive production of fish and crustaceans in these systems is reliant on high-protein feed to facilitate the rapid growth of animals. However, the food conversion ratios of these animals are relatively inefficient resulting in nutrient-rich waste (Crab et al. 2007). For example, in intensive prawn production, only 22 % of the input nitrogen is converted to harvested shrimp whilst the majority (>50 %) is discharged in waste water (Jackson et al. 2003). If released directly into the environment, these waste nutrients can cause significant environmental degradation through nitrogen enrichment and lead to the proliferation of algal growth (Anderson et al. 2012). Therefore, the treatment of waste from land-based aquaculture typically involves a number of steps to manage the breakdown of organic wastes into dissolved inorganic waste products, primarily mineralised nutrients such as nitrogen and phosphorus, which can then be assimilated by algae prior to release of the water (Castine et al. 2013).

Algae, including marine macroalgae (seaweeds), can rapidly increase in biomass when excess nutrients are available. As such, seaweeds can be cultivated in aquaculture waste water to recover a high proportion of these waste nutrients, whilst simultaneously creating a biomass resource (Mata et al. 2010). The integration of seaweed cultivation with land-based aquaculture for nutrient remediation has been successfully demonstrated at a research level numerous times (Neori et al. 1991, 2003; Msuya and Neori 2008; Mata et al. 2010), although rarely implemented commercially (Bolton et al. 2009). One of the major reasons for this is that the seaweed biomass produced requires a market, or on-site use, otherwise the seaweed biomass itself can become a waste product and liability. As such, the viable recovery of nutrients requires the

Electronic supplementary material The online version of this article (doi:10.1007/s10811-015-0544-2) contains supplementary material, which is available to authorized users.

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development of techniques to convert the nutrients within the seaweed biomass into a stable and commercially useable form.

One of the lowest cost approaches to nutrient stabilisation is composting, which is the aerobic decomposition of organic material by successive microbial communities. To successfully compost any organic waste, the carbon-to-nitrogen ratio of the material needs to be balanced. This ratio has some flexibility but most land-based waste is composted using a C:N ratio of between 25:1 and 35:1 (Bishop and Godfrey 1983; Bernal et al. 2009; Han et al. 2014). To achieve this ratio, a high nitrogen biomass such as seaweed can be mixed with a high carbon material, and in many regions agricultural crop residues are an abundant source of carbon-rich biomass. In tropical sugar growing regions, approximately 280 kg of sugarcane bagasse, a fibrous by-product of the sugar extraction process, is produced for every ton of sugarcane material (Cerqueira and Meireles 2007). Utilising agricultural crop residues is also beneficial as the nutrients recovered through seaweed composting can be applied to the next crop cycle.

As seaweed is a relatively novel feedstock for composting, it is unknown as to how the initial C:N ratio of seaweed-based composts will influence the composting process and the quality of the mature compost. Previous studies that have composted seaweeds have used volumetric proportions on a fresh weight basis, with seaweed accounting for between 5 and 85 % of these mixes (Mazé et al. 1993; Cuomo et al. 1995; Eyras et al. 1998; Wosnitza and Barrantes 2006; Winberg et al. 2013). In general, these studies have successfully composted seaweed with a range of materials; however, the use of fresh weight proportions is problematic as both the moisture and nitrogen content of the seaweed biomass will vary. This makes it difficult to either replicate these findings or understand how variation in the initial C:N ratio of seaweed-based composts influences the quality of the mature compost. A thorough understanding of how the initial C:N ratio of the compost mix influences the quality of the mature compost will enable seaweed composting to be applied to any source of seaweed in any location and will facilitate the progression towards the commercial scale production of seaweed composting that produces a consistent and high quality product. This is especially relevant considering the large degree of uncertainty surrounding the quality of mature seaweed composts, including concerns as to whether the high salt content of seaweed composts will have negative effects on crop health and yields (Eyras et al. 2008; Michalak and Chojnacka 2013; Winberg et al. 2013).

The overall aim of this study was to determine if the tropical green seaweed *Ulva ohnoi* (Chlorophyta) cultivated in high-nutrient waste water from prawn (shrimp) farming can be composted with sugarcane bagasse to recover nitrogen and phosphorous from aquaculture effluents for agricultural applications in the co-located sugarcane industry. Specifically, this study firstly investigates how the initial C:N ratio of the seaweed/bagasse mix influences the composting process, time to maturity and the amount of nitrogen and phosphorous lost during the composting process, and secondly, assesses the quality of each of the finished composts and determines whether seaweed-based compost is suitable for use as a plant growth medium and fertiliser.

Methods

Compost feedstocks and procedure

The green seaweed *U. ohnoi* (commonly known as sea lettuce and hereafter referred to as seaweed) was cultured in six 34 m (L)×4 m (W) raceways using the discharge water of an intensive prawn aquaculture facility (Pacific Reef Fisheries Ltd. S19°28′46″, E147°29′18″) in North Queensland, Australia. This biomass was harvested with nets and transported to James Cook University, arriving within 4 h of harvesting. The sugarcane bagasse was supplied from the Home Hill sugar processing facility (S19°39′40″, E147°24′50″) in North Queensland, Australia.

To determine the elemental composition of both the seaweed and bagasse, representative samples were collected prior to the compost trials, dried overnight at 60 °C and analysed for total nitrogen and carbon analysis (OEA Labs, UK). An additional 24 elements including phosphorous were analysed using Inductively Couple Plasma Optical Emission Spectrometry (ICP-OES) by the Advanced Analytical Centre at JCU (Table 1). To understand how seaweed biomass composts and what proportion of bagasse is required to produce a stable decomposition process, eight compost piles were created. The seaweed and bagasse were combined in predetermined dry weight (DW) equivalent proportions based on the total amount of carbon and nitrogen available in each type of biomass. This gave an initial carbon-to-nitrogen ratio of the composts of 11:1, 18:1, 22:1, 26:1, 30:1, 34:1, 40:1 and 50:1. The proportion of seaweed biomass on a DW basis in each compost ranged between 21 and 84 %, which equates to a fresh weight (FW) basis between 55 and 96 % (Table 2). Each of these composts were manually mixed and then added to a 400 L Aerobin static compost bin with a passive aeration pipe in the centre of the bin and a 15-L leachate collection tray in the bottom. Each bin was topped up weekly with fresh seaweed and bagasse at the appropriate ratio, for the first 3 weeks, to account for material compaction.

Compost parameters

During the composting period, the temperature, bulk density (BD), electrical conductivity (EC) and pH were monitored weekly on the wet compost biomass. Temperature was

Table 1 Chemical and physical characteristics of the green seaweed *U. ohnoi* and sugarcane bagasse biomass used to make compost. Moisture content is based on fresh biomass, whilst all other analyses have been performed on dried biomass

	Ulva ohnoi	Bagasse	Units
Carbon	22.27	41.5	wt %
Nitrogen	2.99	0.36	wt%
Moisture content	85	30	wt%
Electrical conductivity	7.15±0.22	0.28±0.03	mS.cm^{-1}
pH	7.19±0.34	4.56±0.12	–
Organic matter	63.17±0.48	83.49±2.53	wt%
Ash content	36.83±0.64	16.51±2.62	wt%
Na	52.33±1.0	0.42±0.10	g Kg^{-1}
S	49.23±0.73	1.18±0.47	g Kg^{-1}
Mg	39.13±0.88	0.58±0.23	g Kg^{-1}
K	30.50±5.67	1.04±0.26	g Kg^{-1}
Ca	4.65±0.47	1.47±0.21	g Kg^{-1}
P	1.59±0.11	0.24±0.002	g Kg^{-1}
Fe	0.78±0.21	2.38±0.75	g Kg^{-1}
Al	0.34±0.089	2.33±0.77	g Kg^{-1}
Mn	53.83±11.84	69.23±19.99	mg kg^{-1}
B	47.97±6.52	≤0.1	mg kg^{-1}
Sr	76.8±9.1	9.28±1.91	mg kg^{-1}
Zn	14.07±2.59	11.84±3.63	mg kg^{-1}
Cu	6.63±0.78	7.41±2.68	mg kg^{-1}
Se	3.44±0.03	≤1	mg kg^{-1}
Cr	2.43±0.11	8.57±3.38	mg kg^{-1}
Ba	2.09±0.32	14.37±3.51	mg kg^{-1}
Ni	1.67±0.11	3.48±1.47	mg kg^{-1}
V	1.49±0.23	5.25±1.29	mg kg^{-1}
As	1.18±0.06	≤1	mg kg^{-1}
Co	0.37±0.07	0.86±0.23	mg kg^{-1}
Pb	0.12±0.01	1.44±0.45	mg kg^{-1}
Mo	0.11	≤0.1	mg kg^{-1}
Cd	0.06±0.001	≤0.05	mg kg^{-1}
Hg	≤0.5	≤0.5	mg kg^{-1}

measured using a 61 cm Heavy Duty Reotemp thermometer at two depths (25 and 50 cm) with three measurements taken at each depth. These six samples were used to provide an average temperature of the entire compost. BD is the measure of the mass (M) of material within a given volume (V) and was calculated on the wet compost using the equation $BD_{wet}= M_{wet}/V_{wet}$, where a 5 L bucket was filled with non-compacted compost material from a depth of 30 cm, excess material was removed until level with the top of the container. This process was replicated three times for each compost treatment. The EC and pH were measured using a HACH HQ40d portable probe using the fresh compost in a 1:10 weight to volume dilution using deionised water. This is the recommended dilution for soils high in organic matter (Carter 1993).

To determine the percentage ash, organic matter, nitrogen and carbon content, a 20 g sample from a depth of 30 cm was taken weekly from each compost and dried overnight at 60 °C and milled to a fine powder. To account for residual moisture in the dried compost samples, a 3 g subsample was heated at 110 °C in a moisture balance until constant weight was reached. The ash content of this biomass was then quantified in duplicate through the combustion of 500 mg of each subsample at 550 °C in a muffle furnace until constant weight was reached. The proportion of organic matter in these subsamples is the fraction that is lost on ignition and is calculated as the difference between initial and final weight of the sample. At the end of the composting period (16 weeks), a further 2 g sample was taken from each compost for elemental analysis by Inductively Couple Plasma Optical Emission Spectrometer (ICP-OES) (Advanced Analytical Centre, JCU, Australia).

To determine the amount of nitrogen and phosphorous that was leached from the compost, the leachate tanks were drained weekly, the total volume measured and a 100 mL sample taken to determine the concentration of ammonium-, nitrite- and nitrate-nitrogen and total phosphorous (Australian Centre for Tropical Freshwater Research, JCU, Australia). To determine the importance of the initial C:N ratio as a predictor of the final quality of the compost, linear regression analysis was used to examine the relationship between the independent variable (initial C:N ratio) and the response variables (bulk density, electrical conductivity, pH, organic matter, carbon content, nitrogen content, and the final C:N ratio) of the mature compost.

Sugarcane growth trial

To examine whether the mature seaweed composts were suitable to use as a soil additive for the sugarcane industry, a pot plant growth trial was undertaken. This growth trial was carried out using pots made from 20 cm long, 10 cm diameter PVC tubes. Each pot was filled with either 100 % compost or a compost:sand mixture based on the volumetric proportions of 25, 50 and 75 % compost. Five replicate pots were used per compost treatment combination. A commercial compost product (King Brown Compost, Mareeba, Australia) made from a mix of chicken manure, bagasse and council green waste was used as a positive control. Each of the five replicate pots were filled with the compost or compost:sand mix, wet to water holding capacity and then allowed to stabilise for 7 days. To determine the concentration of soluble salts in the composts that were leached during this period, 21 additional pots were prepared and filled with 100 % compost from each of the seven mature seaweed composts (n=3). After these pots had stabilised for 7 days, the compost was sampled for pH, EC and salinity.

Forty mature stalks of the Australian commercial sugarcane variety Q253 were freshly cut by the Burdekin Productivity

Table 2 Physical and chemical characteristics of the seven mature seaweed composts and a qualitative score (high, medium, low) based on the overall quality of the compost and their suitability as a soil amendment for agricultural use

Initial C:N	18:1	22:1	26:1	30:1	34:1	40:1	50:1	–
Compost quality	High	High	Medium	Medium	Medium	Low	Low	–
Ulva (%DW)*	60	50	44	38	33	28	21	%
Ulva (%FW)**	87	82	78	74	70	64	55	%
Final C:N	13.78	13.59	19.88	17.85	18.89	24.29	27.96	–
Nitrogen	1.91	1.93	1.30	1.53	1.44	1.09	1.05	wt%
Carbon	25.97	26.36	25.35	27.43	25.86	24.63	27.67	wt %
Electrical conductivity	10.31	9.37	10.17	9.23	10.15	10.18	8.37	mS.cm^{-1}
pH	8.9	5.88	6.06	5.9	6.9	6.8	6.5	–
Organic matter	58.6	56.3	55.6	59.4	58.7	58.5	56.4	wt%
Na	28.87	28.01	27.06	23.96	18.61	16.79	10.60	g kg^{-1}
Mg	27.27	24.8	22.67	18.97	14.90	15.20	10.80	g kg^{-1}
S	25.80	23.3	23.6	19.43	15.69	24.33	11.92	g kg^{-1}
K	15.90	15.6	16.17	13.10	10.40	15.50	7.96	g kg^{-1}
Ca	5.10	4.46	4.16	3.26	3.80	2.80	3.05	g kg^{-1}
Fe	3.60	3.71	3.35	3.13	3.80	3.02	4.14	g kg^{-1}
Al	3.86	3.77	4.00	4.01	4.50	3.51	4.68	g kg^{-1}
P	1.29	1.23	1.11	1.05	0.99	0.96	0.76	g kg^{-1}
Mn	110.67	104.24	99.17	100.13	135.0	97.23	119.00	mg kg^{-1}
B	95.13	88.62	38.87	43.07	21.19	39.57	37.30	mg kg^{-1}
Sr	59.5	50.31	44.50	40.47	38.76	39.2	29.90	mg kg^{-1}
Zn	31.43	21.12	23.93	21.40	24.03	45.57	21.97	mg kg^{-1}
Cr	9.60	10.78	13.80	12.56	17.73	26.27	42.27	mg kg^{-1}
Ba	17.2	16.1	19.23	18.17	23.53	18.23	23.33	mg kg^{-1}
Cu	9.79	9.52	9.27	8.75	8.77	8.03	8.04	mg kg^{-1}
V	8.80	9.16	10.62	9.62	11.3	10.65	11.38	mg kg^{-1}
Ni	7.64	6.62	5.77	4.71	5.35	6.61	9.86	mg kg^{-1}
Se	1.91	2.39	1.60	1.49	0.99	1.58	0.85	mg kg^{-1}
As	1.87	1.62	1.56	1.36	1.45	1.42	1.45	mg kg^{-1}
Co	1.86	1.50	1.66	1.52	2.00	1.53	2.43	mg kg^{-1}
Pb	1.6	1.58	1.53	1.47	1.89	2.01	2.07	mg kg^{-1}
Mo	0.40	0.38	0.29	0.34	0.42	0.25	0.36	mg kg^{-1}
Cd	0.08	0.06	≤0.05	≤0.05	≤0.05	≤0.05	≤0.05	mg kg^{-1}
Hg	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	≤0.5	mg kg^{-1}

*Proportion of *Ulva* in the initial compost mix based on the dry weights of both *Ulva* and bagasse

**Proportion of *Ulva* in the initial compost mixes based on as received fresh weight, *Ulva* 85 % moisture, bagasse 30 % moisture content

Services and transported to JCU. These mature stalks were then cut into single-eye sets and germinated in seedling trays (400×400×90 mm) containing washed river sand. Once these plants were between 100 and 170 mm high, 160 uniform seedlings were randomly transplanted into the compost mixtures. The initial size of cane seedlings did not differ significantly between treatments groups (PERMANOVA $F_{31,\ 128}$= 0.66, P=0.92). The trial was undertaken in a shade house (50 % shade cloth), to provide uniform diffuse sunlight to all pots. This trial was conducted over a 10 week period between 8 April and 17 June 2014 and during this period, the daily air temperatures ranged between 19.4 and 30.1 °C and mean daily photosynthetic active radiation of 21.2 (±1.1) mol photons m^{-2}, (range: 4.7–41.7 mol photons m^{-2}) with daily (0600–1800 hours) peaks ranging between 354.4 and 2,025.8 μmol photons m^{-2} s^{-1}.

At the end of the growing period, the total height (measured from the base node to leaf tip), the number of cane stalks per plant and the width of the main stalk (at its widest point) were measured. The plant was then cut from the base node and air-dried at 60 °C and weighed to give the total above-ground biomass. To account for variation in the initial biomass of the transplanted cane seedlings, a height to DW relationship was determined for the germinated cane plants ($n=78$) that were not used in this experiment, these cane plants spanned a height of 60–300 mm. Cane plant height explained 69 % of the variation in DW (Supp. A), using the equation $y=0.001x+0.61$, an estimate of the initial DW was subsequently calculated for each of the 160 cane seedlings used in the growth trial, with this amount subtracted from the final weight of above-ground biomass from each replicate. The relative quality of each compost mixture was compared using DW growth rates (g DW day^{-1}) that were calculated by dividing the total above-ground DW biomass by the length of the growth trial (70 days). The roots and soil could not be satisfactorily removed to give an accurate measure of below-ground biomass but the relative difference in the mass of the root ball in each compost treatment can be seen in Supp. (B).

We used a two-factor permutational analysis of variance (PERMANOVA) to analyse the effects of initial C:N ratio of the compost and the proportion of compost in pots, regarded as fixed factors, on four variables: the total height, width of the main stalk, total number of stalks per plant and the total above-ground biomass of sugarcane plants. PERMANOVA is a technique to partition total sums of squares from a single or multifactorial experimental design using multivariate data and to test for statistical differences between groups (Anderson 2001, McArdle and Anderson 2001). The method is nonparametric, estimates a distance-based pseudo-F statistic, and subsequently determines P values based on permutational procedures. All PERMANOVA tests presented here are based on 10,000 permutations, using type III sums of squares and permutation of residuals under a reduced model undertaken using Primer 6 and the PERMANOVA+add on (Anderson et al. 2008). Due to the number of potential pairwise comparisons (156 per plant response variable) in the experimental design, we have not presented individual comparisons when significant interactions were detected but instead use variance components (% variance explained: η^2) to interpret the relative importance of the significant terms in the models.

Results

Compost feedstock

Seaweed (*U. ohnoi*) and sugarcane bagasse had very different physical and chemical compositions (Table 1). Seaweed had a mean (±1 standard error) nitrogen content of 2.99 (±0.24) %, carbon content of 22.27 (±0.99) % and a C:N ratio of 7.5:1. This seaweed was also characterised by a high EC (7.15 mS.cm^{-1}), a neutral pH (7.19±0.34) and a relatively high ash content of 36.83 (±0.64) %, predominantly composed of sodium, sulphur, magnesium and potassium (Table 1). In contrast, the sugarcane bagasse had a very low nitrogen content of 0.36 (±0.05) %, a high carbon content of 41.5 (±0.84) % and a C:N ratio of 115:1. The bagasse was characterised by a low EC (0.28±0.03 mS.cm^{-1}) and an acidic pH (4.56±0.12). The ash content of the bagasse was also relatively low and averaged 16.51 (±2.62) % with the main elements in this ash being iron, aluminium, calcium, sulphur and potassium (Table 1). Sodium, sulphur, magnesium and potassium concentrations in seaweed were between 30 and 125 times that of the bagasse, whereas iron and aluminium concentrations in bagasse were between 3 and 7 times that of the seaweed.

Compost parameters

Of the eight seaweed-bagasse mixtures, all but one was successfully converted into mature compost. The compost mix with an initial C:N ratio of 11:1 (84 % seaweed DW) became anoxic and putrid and was terminated after 8 weeks. The remaining seven seaweed-bagasse combinations all produced viable mature compost within 16 weeks, although the physical parameters during the composting process varied along with the mature compost profiles (following section).

The temperature profiles of all seven composts were very similar with temperatures ranging between 45.3 (±3.8) and 51.6 (±3.7) °C for the first 21 days of decomposition (Fig. 1a). There was a slight trend of increasing temperatures with increasing proportion of seaweed (decreasing initial C:N ratio) although this was predominantly driven by the highest bagasse treatment (initial C:N 50:1) which consistently had the lowest temperatures. Regardless, this compost mixture still maintained a temperature above 45 °C for the first 21 days of decomposition. All compost mixes cooled steadily between days 21 and 56 until they reached the average ambient daytime temperature of 31 °C where they remained for the remainder of the composting period (Fig. 1a). The compost with an initial C:N ratio of 18:1 took the longest to cool with temperatures up to 35.3 (±0.6) °C still recorded at day 70 and this compost was consistently 1–2 °C warmer than the other piles up to day 100 (Fig. 1a).

The EC was high in all of the compost treatments. The initial EC of the seven compost treatments ranged between 4.43 (±0.45) and 9.11 (±0.41) mS.cm^{-1} and increased through the composting period to a stable conductivity for each compost that ranged between 8.37 (±0.24) and 10.31 (±0.68) mS.cm^{-1}, with the highest conductivities in the compost treatments with the highest proportions of seaweed, i.e. those with the lowest initial C:N ratios, although this effect was not significant (regression, $R^2=0.31$, $P=0.20$) (Fig. 1b).

The pH of the compost treatments showed slightly more divergence than temperature and EC (Fig. 2a). During the first 42 days of composting the pH ranged between 5.33 (±0.01) and 8.98 (±0.01). After this time point, the pH of the composts separated into two groups, the high seaweed compost (initial C:N of 18:1) maintained a high pH that ranged between 8.71 (±0.01) and 9.03 (±0.02). In comparison, the variation in pH

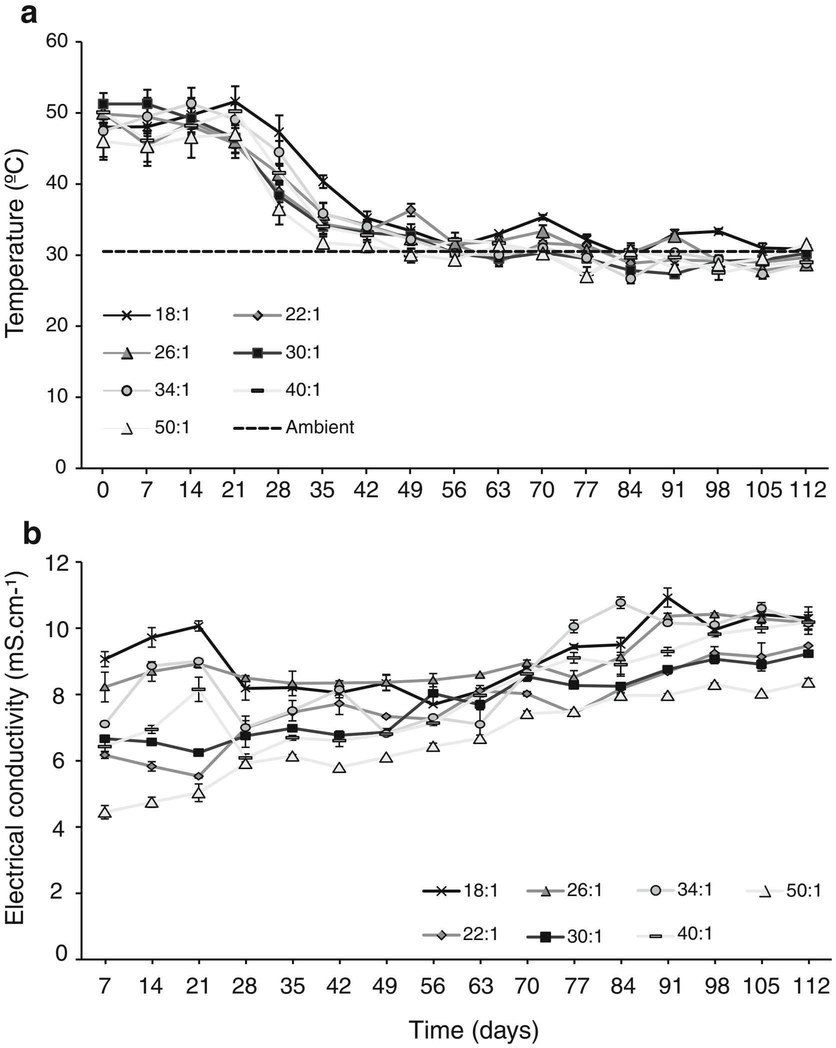


Fig. 1 Changes in **a** temperature and **b** electrical conductivity (EC) of seven seaweed-based composts during a 112-day composting period. The proportion of seaweed added to each bin was manipulated to control the initial C:N ratio of each compost. Data are the mean and standard error of the analytical replicates of each compost

measurements among the remaining six compost treatments reduced greatly beyond day 42 and converged on a final pH that ranged between 5.98 (±0.03) and 6.93 (±0.01) (Fig. 2a). The initial C:N ratio of the composts did not have a significant effect on the pH of the mature composts (regression, R^2=0.08, P=0.540).

The bulk density was highly variable both among and within compost treatments during the initial composting period. On day 0, bulk density ranged between 259.60 (±17.8) and 399.01 (±14.53) kg.m^{-3} and generally increased through time (Fig. 2b). The between treatment variation in bulk density was highest on day 28, ranging between 367.67 (±14.67) kg.m^{-3} in the low seaweed (50:1) compost to 824.44 (±21.37) kg.m^{-3} in the high seaweed (18:1) compost treatment. However, the variation in these measurements decreased rapidly after day 42 and by day 77 the bulk density had stabilised with very little change beyond this point (Fig. 2b). The final bulk density of the seven composts ranged between 355.87 (±9.48) kg.m^{-3} and 609.47 (±6.69) kg.m^{-3} and was significantly affected by the initial C:N ratio of the composts (regression, R^2=76, P=0.011). In general, the lower the initial C:N ratio or the higher the proportion of seaweed in the compost mix then the higher the final bulk density (Fig. 2b).

The proportion of organic matter in each of the composts exhibited a steady 5–15 % decline over the 112-day composting period. At day 0, the composts had an organic matter content that ranged between 59.21 (±0.19) and 67.15 (±0.82) % and ended the composting period with an organic matter content that ranged between 55.64 (±1.79) and 59.35 (±2.09) % (Table 2). The final organic matter content of the composts was not dependent on the initial C:N ratio (regression, R^2=0.002, P=0.92)

Mature compost profiles

The initial C:N ratio had no significant effect (regression, R^2=0.06, P=0.6) on the carbon content in the mature composts, with all seven seaweed composts having a carbon

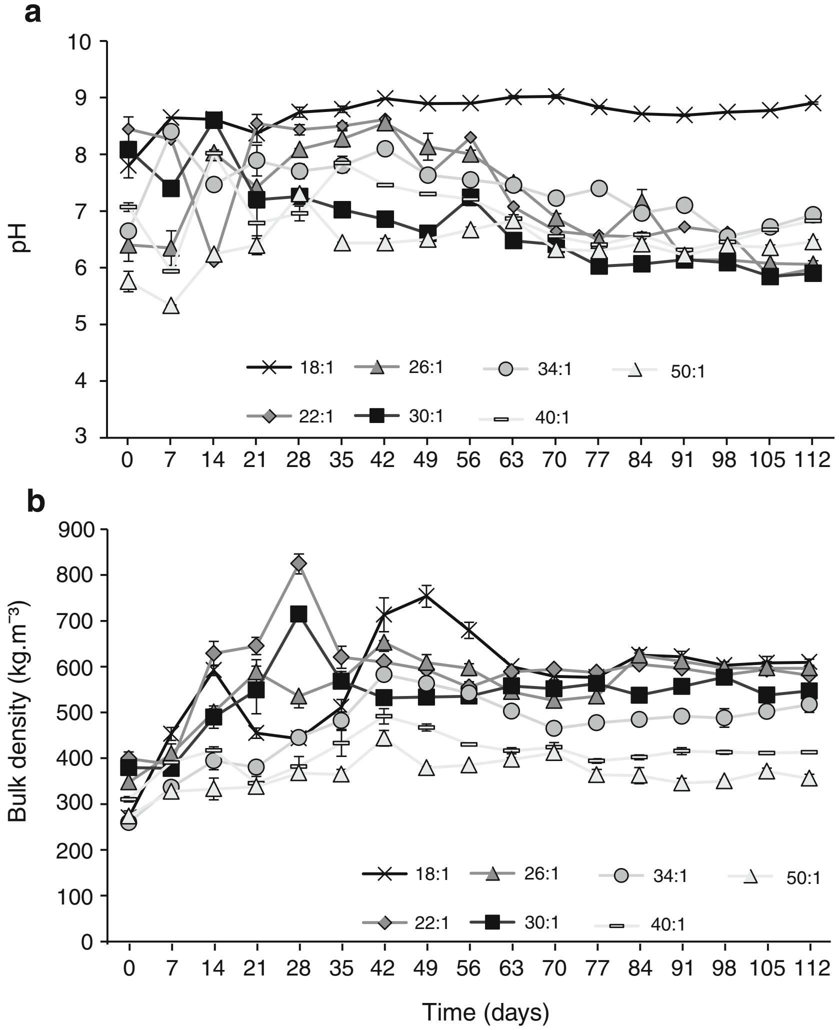


Fig. 2 Changes in **a** pH and **b** bulk density of seven seaweed-based composts during a 112-day composting period. The proportion of seaweed added to each bin was manipulated to control the initial C:N ratio of each compost. Data are the mean and standard error of the analytical replicates of each compost

content that ranged between 25.35 (±0.77) and 27.67 (±0.69) %. In contrast, the nitrogen content (regression, $R^2=0.76$, $P=0.01$) and the final C:N ratio (regression, $R^2=0.90$, $P=0.0001$) of the mature composts were correlated with the initial C:N ratio of each compost and, in general, both the final C:N ratio and the nitrogen content in the mature composts decreased as the initial C:N ratio of the compost mixes increased (Table 2). The seven composts could be split into three distinct groups based on the total nitrogen content of the mature composts. Firstly the highest quality composts with an initial C:N ratio of 18 and 22:1 had the highest nitrogen concentrations, with 1.91 (±0.01) and 1.93 (±0.01)% DW of these composts consisting of nitrogen. These two composts had a final C:N ratio of 13.78 (±0.2) and 13.59 (±0.2):1 respectively. The second group of composts was of medium quality, with an initial C:N ratio of between 26 and 34:1 had a final nitrogen content that ranged between 1.30 (±0.02) and 1.53 (±0.02) %. These composts had a final C:N ratio that ranged between 17.85 (±0.7):1 and 19.88 (±0.9):1. The final group was the low quality compost which consisted of the high bagasse composts that had an initial C:N of 40 and 50:1, had a final nitrogen content of 1.09 (±0.1) and 1.05 (±0.1)% DW respectively and a final C:N ratio of 24.29 (±2.8):1 and 27.96 (±1.6):1 (Table 2). The total phosphorous concentration in the mature composts exhibited a similar pattern to nitrogen and increased as the proportion of seaweed in the composts increased. The concentration of phosphorous in the mature composts ranged from 1.23 (±0.31) and 1.29 (±0.21) $g.kg^{-1}$ in the high quality composts to a low of 0.76 (±0.21) $g.kg^{-1}$ in the low quality compost (initial C:N 50:1) (Table 2).

The elemental composition of the mature composts were broadly similar (Table 2), although all of the elements that were naturally high in the seaweed biomass; sodium, magnesium, sulphur, potassium and calcium, increased in the composts as the proportion of seaweed increased. Sodium, magnesium and sulphur were the three most abundant mineral elements in the mature composts. The concentrations of sodium, magnesium and sulphur ranged from highs of 28.87 (±2.09), 27.27 (±1.93) and 25.8 (±0.81) $g.kg^{-1}$ in the high seaweed compost (initial C:N of 18:1) to lows of 10.60 (±0.22), 10.80

(±0.12) and 11.92 (±0.78) g.kg^{-1} in the high bagasse composts respectively (Table 2). The composts with the highest proportions of bagasse (initial C:N, 40 and 50:1) had higher concentrations of the major elements iron and aluminium but also much higher chromium and relatively high lead, vanadium and cobalt, relative to the trace elements in other composts.

Nitrogen and phosphorous accounting

The total amount of nitrogen added to each of the 7 composts ranged from 0.4 kg per mix in the compost with a C:N of 50:1 to 1.37 and 1.32 kg in the composts with an initial C:N ratio of 18 and 22:1. Each of the mature composts lost nitrogen through the composting process, with the amount and proportion of nitrogen lost increasing as the initial C:N ratio decreased. The largest amount of nitrogen was lost from the compost with an initial C:N ratio of 18:1, with this compost losing 678 g (48.6 %) of its initial nitrogen, whilst the composts with a starting ratio of 22, 26 and 30:1 lost 108.0 g (8.0 %), 308.8 g (27.5 %) and 103.4 g (8.5 %) of their initial nitrogen respectively. The composts that had an initial C:N ratio higher than 30:1 lost less than 20 g of nitrogen through the composting process. Of this lost nitrogen only a small fraction (<5 %) was lost through leaching. However, the amount of nitrogen leached did increase as the initial C:N ratio decreased. The total amount of nitrogen lost via leaching was 52, 27.8, 5.2 and 10.2 g for the composts with an initial C:N ratio of 18, 22, 26 and 30:1 respectively. No nitrogen was lost through leaching for the composts that had an initial C:N ratio greater than 30:1. The majority of nitrogen (>95 %) that was lost from the composts was unaccounted for and was most likely volatilised. All composts that had an initial C:N ratio of less than 30:1 had a strong ammonia aroma during the composting period with the strength of the ammonia aroma increasing as the C:N ratio decreased.

The initial amount of phosphorous in each of the composts ranged from a low of 24.2 g in the compost with the highest proportion of bagasse to highs of 70.1 and 75.3 g in the high seaweed composts. Phosphorous was leached from all of the composts that had a starting C:N ratio of less than 30:1, with the amount of phosphorous leached increasing as the proportions of seaweed in these composts increased. The composts that had an initial C:N ratio of 18 and 22:1 leached 302 and 276 mg over the composting period. The remaining two composts that leached phosphorous had an initial C:N ratio of 26 and 30:1 with each leaching 127 mg of phosphorous over the composting period. These losses represent between 0.18 and 0.75 % of the total phosphorous added to these composts.

Sugarcane growth trial

The characteristics of each compost changed during the 7 days after being added to the pots and wet to water holding capacity. The pH of these composts after stabilising generally increased and approached a neutral pH, with a final pH ranging between 6.5 and 8.2. The salinity decreased from 4.6–7.1 ppt to between 0 and 1.3 ppt and the EC of each compost decreased by between 4 and 12 fold, with all composts having a final EC of less than 2.7 μS.cm^{-1}, with the largest decrease in the high seaweed composts (Supp. C).

All seven seaweed composts were suitable substrates for sugarcane growth. However, there was a significant interaction between the initial C:N ratio of the composts and the proportion of compost that was added to each pot which influenced the height of sugarcane plants (PERMANOVA, $F_{21,128}=3.42$, $P<0.001$), the width of the main stalk (PERMANOVA, $F_{21,128}=2.62$, $P<0.001$), the number of stalks per plant (PERMANOVA, $F_{21,128}=2.07$, $P<0.001$) and the total above-ground DW biomass (PERMANOVA, $F_{21,128}=4.59$, $P<0.001$) (Supp. D). In general, all of the growth parameters increased as the proportion of seaweed in the initial compost mix increased, with the exception that all growth parameters were depressed using compost with an initial C:N ratio of 26:1 relative to the other composts (Figs. 3, 4). In this compost the total above-ground biomass (DW) was 3 times lower than the composts that had an initial C:N ratio of 18, 22 and 30:1 (Fig. 3). Due to the large number of pairwise comparisons in the experimental design, we have not presented individual comparisons. Even though there were significant interaction terms for each variable (meaning that individual pairwise comparisons are inappropriate), it is clear that the driving force of the interaction is consistently the effect of 26:1 and 100 % compost (Total above-ground biomass=6.06 g (26:1) vs 23.02 and 16.44 g in the 22 and 30:1 treatments)(Figs. 3 and 4). The majority of the variance for each response variable, between 71 and 81 %, was in each case explained by the main effect of the initial C:N ratio of the compost, whilst only 15–23 % of the variance in sugarcane growth was explained by the proportion of compost in each pot which is shown in the full output (Supp. D).

In each compost treatment the sugarcane grown in 100 % compost outperformed the treatments mixed with sand, with this effect most pronounced in the low seaweed composts that had an initial C:N ratio of more than 34:1 (Figs. 3, 4). This effect can also be seen in the size of the root mass which decreased as both the proportion of seaweed in the initial compost mix decreased and as the proportion of sand in the pots increased (Supp. B). Sugarcane grown in 100 % compost (no sand treatments) had a total plant height that ranged between 865 (±24.9) mm in the low seaweed composts to 1,551.0 (±21.8) mm and 1,588.2 (±30.6) mm in the high seaweed composts that had an initial C:N ratio of 18 and 22:1 (Fig. 3a). The width of the main stalk of the sugarcane doubled from 9.3 (±0.4) mm in the low seaweed compost to 17 (±0.5) mm and 18.1 (±0.5) mm in the high seaweed composts (Fig. 3b). Likewise, the average number

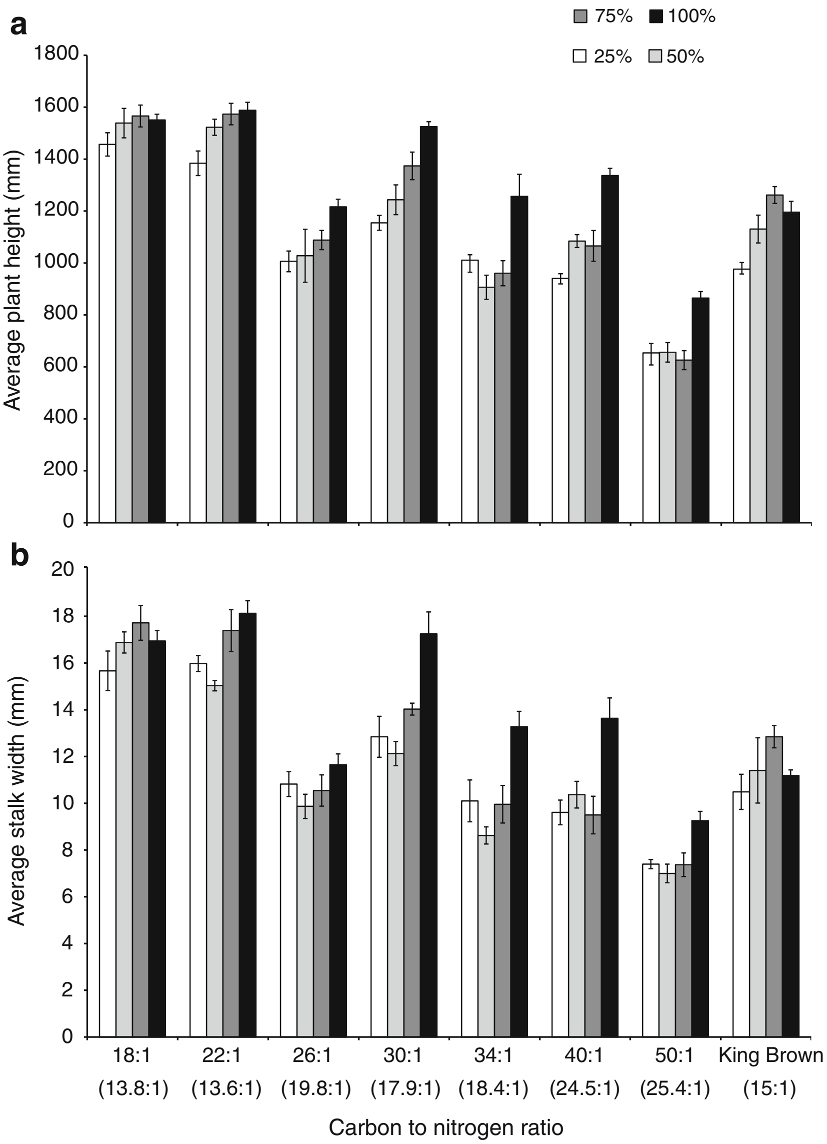
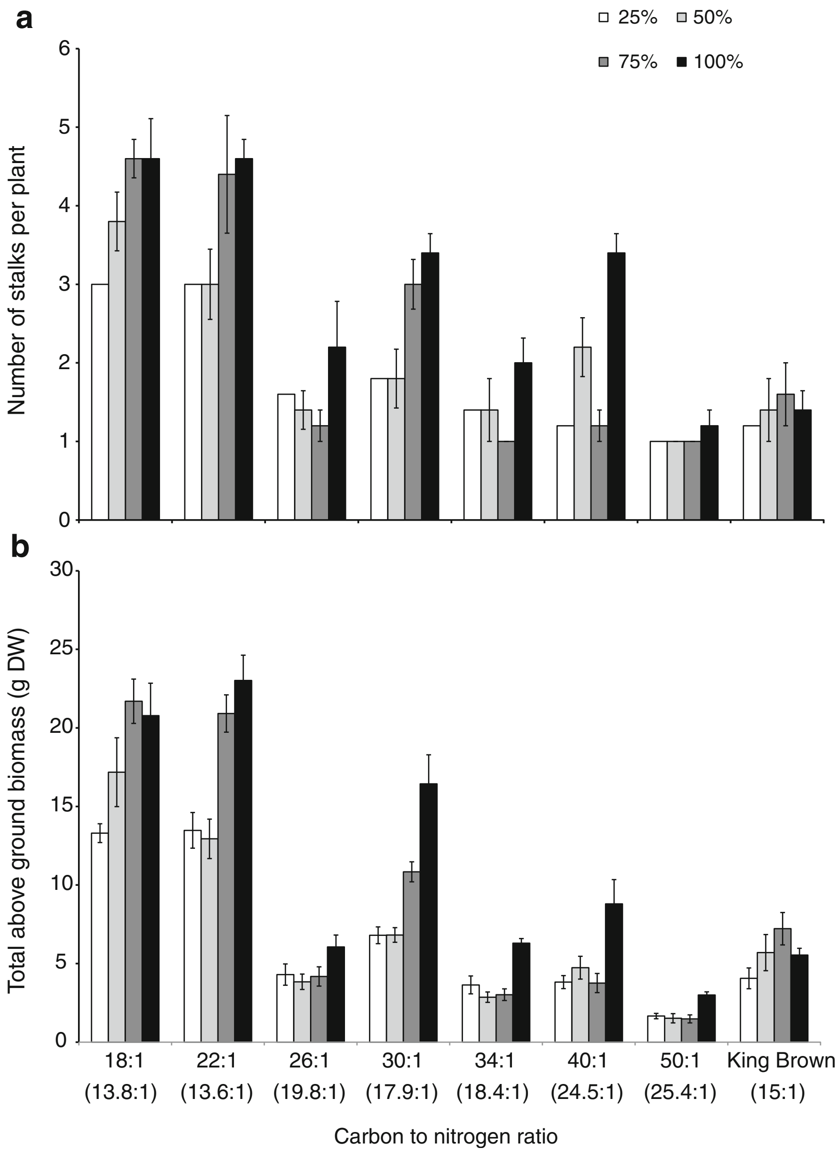


Fig. 3 The average±standard error of **a** height and **b** width of the main stalk of sugarcane grown in seven seaweed-based composts. Seaweed was included in varying proportions to manipulate the initial carbon-to-nitrogen ratio of the compost material. The *x-axis* has the initial carbon-to-nitrogen ratio of each compost mix and *in parenthesis* the final carbon-to-nitrogen ratio of the mature compost that was used in this trial. King Brown is a commercial compost which contains no seaweed and was used as a positive control

of stalks per plant increased 4-fold from 1.2 (±0.2) to 4.6 (±0.5) stalks between the low and high seaweed composts respectively (Fig. 4a). The total above-ground biomass increased sevenfold from 3 (±0.2) g DW in the low seaweed compost to highs of 20.8 (±2.8) and 23.2 (±1.6) g DW in the two composts with the highest proportions of seaweed (Fig. 4b). This gave a net rate of above-ground growth that ranged between lows of 0.04 (±0.003) g DW.day^{-1} in the low seaweed compost to highs of 0.29 (±0.03) and 0.33 (±0.02) g DW.day^{-1} in the high seaweed composts. In comparison, the control compost (no seaweed) was similar to the intermediate seaweed composts which had an initial C:N ratio that was greater than 34:1. Sugarcane grown in 100 % control compost had an average plant height of 1, 195.6 (±41.6) mm, a stalk width of 11.2 (±0.2)mm, 1.4 (±0.2) stalks per plant, a total above-ground biomass of 5.54 (±0.43) g DW and net rate of above-ground biomass production of 0.08 (±0.01) g DW.day^{-1}.

In general, all of the sugarcane growth metrics exhibited a linear decline as the proportion of sand in the compost:sand mix increased, with this effect greatest in the low seaweed composts which had a high initial C:N ratio (Figs. 3, 4). The exception to this were the two composts that had the highest proportions of seaweed (initial C:N of 18 and 22:1) which had very little difference in stalk length and width between the four compost sand mixes (Fig. 3a, b), but there was still a 30–40 % reduction in the total above-ground biomass (Fig. 4b). Moreover, in these high seaweed composts, a 25 % compost:sand mix resulted in an equivalent or higher rate of growth than many of the sugarcane plants grown in the 100 % compost treatments of the low seaweed composts (Figs. 3, 4). Sugarcane grown in the

Fig. 4 The average±standard error of the **a** number of stalks per plant and **b** total above-ground biomass of sugarcane plants grown in seven seaweed-based composts. Seaweed was included in varying proportions to manipulate the initial carbon-to-nitrogen ratio of the compost material. The *x-axis* has the initial carbon-to-nitrogen ratio of each compost mix and *in parenthesis* the final carbon-to-nitrogen ratio of the mature compost used in this growth trial. King Brown is a commercial compost which contains no seaweed and was used as a positive control



25 % high seaweed composts had a total above-ground biomass of 13.3 (±0.6) and 13.5 (±1.1) g DW which was between 1.5- and 3-fold higher than the sugarcane grown in 100 % of either the low seaweed composts or the control compost (Fig. 4b).

Discussion

This study has demonstrated that the nutrients from seaweed cultivated in the waste water of land-based aquaculture can be successfully transformed through composting into a high quality soil additive within 16 weeks. The regular application of compost to soil can improve its physical, chemical and biological characteristics (Flavel and Murphy 2006). However, for these benefits to occur, the quality of the compost needs to be high. In this study, the initial C:N ratio of each compost was a significant predictor in the quality of the mature compost as demonstrated by the clear trend of the decreasing final C:N ratio and increasing nitrogen content in the mature compost as the initial C:N ratio was decreased. Both the total nitrogen content and the final C:N ratio are important determinants of the usefulness of compost as a source of nitrogen for crop production (Flavel and Murphy 2006). Previous work on plant- and manure-based composts has demonstrated that composts with a final C:N ratio of more 20:1 can limit the amount of nitrogen that is available to plants, as any mineralised nitrogen is rapidly incorporated into the microbial biomass, which in turn use it to continue the breakdown of carbon (Mathur et al. 1993; Bernal et al. 2009). In contrast, when the final C:N ratio of composts is less than 20:1, the growth of microbial biomass is slowed and plants are able to access the mineralised nitrogen (Harada et al. 1981; Tognetti et al. 2007). In this study, five of the mature composts had a final C:N ratio that was less than

20:1, but only two of these composts, those with the highest proportions of seaweed, consistently resulted in a large positive effect on sugarcane growth. Moreover, as the final C:N ratios of these five composts increased towards 20:1, the growth of sugarcane decreased considerably. This indicates that the final C:N ratio of seaweed-based compost should, as a minimum, be less than 18:1 to be useful as a soil additive and ideally less than 14:1. In this study, only two composts, those with the highest initial proportions of seaweed, achieved these desired ratios (Table 2).

The initial C:N ratio of the seaweed-based composts also had a major influence on the proportion of nitrogen that was lost during the composting process, which should be considered if the efficiency of nutrient recovery from the waste water is important. Very little nitrogen was lost through leaching but a considerable fraction of the input nitrogen was volatilised in some of the seaweed composts. This was most pronounced in the compost that had the highest proportion of seaweed (initial C:N, 18:1) which lost just under half of the total nitrogen added to this compost. Despite this, the other high seaweed compost (initial C:N, 22:1) performed considerably better, losing only 8 % of its initial nitrogen content. Several factors can influence the proportion of nitrogen lost to the atmosphere. Nitrogen in the form of ammonia (NH_3) is more likely to be volatilised at higher pH levels (>7.5), with temperature accelerating this process (Paredes et al. 2000; Sánchez-Monedero et al. 2001). The main difference between the two high seaweed composts in this study was their pH. The compost with the highest nitrogen losses had a pH that was consistently high and ranged between 8 and 9. In contrast, the high seaweed compost which had a low loss of nitrogen had a more variable, but lower pH through time, decreasing to just below 6 as this compost matured. Despite the large variation in the total amount and proportion of nitrogen that was lost between the composts, these seaweed composts compare relatively well to those made from animal manures, which can lose from 5 to 85 % of their nitrogen during decomposition (Barrington et al. 2002; Ogunwande et al. 2008; Bernal et al. 2009). As such, the nutrient recovery from waste water by seaweed and their subsequent transformation through composting is a relatively efficient technique and can be enhanced by controlling the pH through the addition of sufficient bagasse.

All seven mature seaweed-based composts had a high EC (8–10.4 mS.cm^{-1}); however, this did not ultimately affect the growth rate of sugarcane plants. Notably, the soluble salts were rapidly leached as they were not bound to the matrix of organic compounds in the compost. It is expected that a similar leaching of salts would occur on any free draining soil but in poorly drained clay or sodic soils or in areas with low natural rainfall these soluble salts, especially the high sodium concentrations, could be problematic (Qadir and Oster 2004). In an attempt to reduce this problem previous studies have washed the seaweed biomass prior to composting in an effort to reduce the total amount of salt entering the compost (Cuomo et al. 1995; Wosnitza and Barrantes 2006; Mohee et al. 2013). In these studies washing reduced the conductivity of their composts by as much as 50 %, however, the EC were still relatively high (3–14 mS.cm^{-1}) and the total amount of freshwater consumed in this process is excessive and unsustainable (Cuomo et al. 1995; Wosnitza and Barrantes 2006; Mohee et al. 2013). Moreover, whilst the EC of our composts were high, they are comparable to many terrestrial based composts that have been produced using municipal wastes, which range between 1 and 9 mS.cm^{-1} (Hargreaves et al. 2008) or from animal manures which can range between 3 and 21 mS.cm^{-1} (Wang et al. 2004; Bustamante et al. 2008; Ko et al. 2008). An alternative technique to reduce the EC of all of these composts could be to increase the cation exchange capacity of the composts through the addition of biochar (Zhang and Sun 2014). Biochar is a stable recalcitrant form of carbon that has a very high surface area and subsequently a large number of bonding sites for cations. Importantly, increasing the cation exchange capacity would not inhibit the leaching of sodium, which as a strongly hydrated monovalent cation is relatively mobile in soils and is preferentially displaced on these bonding sites by the cations of calcium, magnesium and potassium (Arienzo et al. 2012) which are important elements that can improve soil structure and promote plant growth (Qadir and Oster 2004; Laird et al. 2010).

Agriculture is a major consumer of nitrogen fertiliser and although compost has been recognised as a potential alternative to synthetic fertilisers, concerns about the cost, consistency and quantities required have resulted in only limited use of compost as a source of nitrogen in agricultural production (Quilty and Cattle 2011). In tropical Australia, the two main agricultural crops, sugarcane and bananas, both consume large quantities of nitrogen fertiliser, typically in the form of urea (46 % N) as it is the most cost effective source (Armour et al. 2013). The recommended guidelines for nitrogen application vary between regions, but the mean annual application rates in tropical Australia are 138 kg.ha^{-1} for sugarcane and 310 kg.ha^{-1} for bananas (Armour et al. 2013; Thorburn and Wilkinson 2013). To provide the equivalent nitrogen to these crops as urea, the optimal seaweed compost (1.93 % N DW) would need to be applied at a rate of 7.2 t DW.ha^{-1} for sugarcane and 16 t DW.ha^{-1} for bananas. The moisture content of the composts was ~65 %, which equates to a fresh weight rate of application of 20.6 and 45.7 t.ha^{-1} or roughly 34.3 and 76.2 m^3.ha^{-1} for sugarcane and bananas respectively. However, basing the application rate on replacing the nitrogen in urea is problematic as a major fraction, up to 65 %, of the applied nitrogen in urea is not utilised by crops but rather is lost to the atmosphere through volatilisation or leached into the groundwater (Armour et al. 2013; Thorburn and Wilkinson 2013). Moreover, a large fraction of the nitrogen in compost is incorporated into organic compounds and in contrast to synthetic fertilisers is not released as a pulse of mineralised nitrogen (Raun and Johnson 1999; Golabi et al. 2007). This creates two major advantages relative to synthetic nitrogen sources, firstly it reduces the proportion of nitrogen that is held in a leachable form and secondly it means that compost effectively acts as a slow release fertiliser with the potential of providing nitrogen over a much longer timeframe (Flavel and Murphy 2006). In general approximately 15–30 % of the nitrogen in composts is available for plants within the first year, with nitrogen mineralization rates of 2–8 % occurring for the next several years (Flavel and Murphy 2006).

Australian agricultural soils are in general old, weathered and typically have low natural fertility. To maintain agricultural productivity on these soils numerous elements in addition to nitrogen need to be supplied (Naidu and Rengasamy 1993; Tilman et al. 2002; Lambers et al. 2008). Seaweed compost is a relatively novel way to supply a range of macro- and micro-nutrients, and trace elements to cropland soils. If the seaweed-based composts were applied to sugarcane at the above rates they would also supply 9.3 kg.ha^{-1} or phosphorous, 114.5 kg.ha^{-1} of potassium, 196.3 kg.ha^{-1} of magnesium, 185.8 kg.ha^{-1} of sulphur, 36 kg.ha^{-1} of calcium and 25.9 kg.ha^{-1} of iron, all important nutrients for plant production (Kirkby 2012). The high seaweed composts are also a good source of several trace elements such as manganese, zinc and boron which are all important for sugarcane production (Evans 1959; Alloway et al. 2008). Unfortunately, at these application rates the high seaweed composts will also supply 207.8 kg.ha^{-1} of sodium to the soil. However, this may not necessarily be detrimental to crops. At these application rates, compost ploughed into the top 30 cm of soil will on a proportional basis account for less than 1 % of the total soil mass with the sodium cations rapidly leached from free draining soils (Rengasamy 2002). As sugarcane is a multi-year crop a potential management practice could be to apply seaweed-based composts in the first year of planting and subsequently apply a smaller quantity of urea to meet demand for each subsequent ratoon crop. Moreover, the application of this compost could be managed such that it was applied prior to planting following a fallow period or a cover crop where it could potentially act as a mineral herbicide, killing weeds prior to being ploughed into the soil and sugar cane subsequently planted.

Another aspect of seaweed that has gained significant attention in the literature is the use of seaweed extracts to enhance plant growth rates (Craigie 2011; Calvo et al. 2014). Seaweeds contain hormones and sterols, such as cytokinins, auxins and gibberellins among others, that stimulate growth in the seaweed (de Nys et al. 1991; Stirk et al. 2009) and can also act as growth promoters in terrestrial plants (Khan et al. 2009; Craigie 2011; Calvo et al. 2014; Stirk and Van Staden 2014). Importantly these seaweed extracts are applied at low rates and these effects are not linked to the increased supply of macro- and micro-nutrients (Stirk et al. 2014). In this study, as the proportion of seaweed in the composts increased, the beneficial effects on sugarcane growth rates also increased. This effect was most pronounced for the composts with the highest proportions of seaweed for which, even at low application rates (25 % compost), the growth response of sugarcane was 1.5–3 times higher than that of sugarcane grown in 100 % of either the control or low seaweed-based composts (Fig 4b). Although the relative differences in nitrogen content and availability between the composts are likely to have influenced this result, the magnitude of this growth effect indicates that it is unlikely to be the sole cause. Rather it indicates that the growth promoting compounds in seaweeds are conserved during the composting process and are bioavailable through the soil. This suggests that the benefits to agriculture from the application of seaweed composts could be considerably higher than merely a mechanism to recover and supply nitrogen, and phosphorus to crops.

In conclusion, this study has demonstrated that unprocessed seaweed biomass, produced in the nutrient-rich waste water of an intensive prawn farm can be combined with a high carbon agricultural waste product and transformed within 16 weeks into a compost of high quality. This study has identified the optimal initial C:N ratio for seaweed-based composts to be 22:1, which corresponds to seaweed accounting for 82 % of the compost on a fresh weight basis. The use of these ratios will ensure that both the quality of the mature compost is high and that nitrogen in the seaweed biomass is conserved, with less than 10 % of this nitrogen lost during the composting process. Reducing the initial C:N ratio to 18:1 will still produce a high quality compost but the proportion of nitrogen that is volatilised increases and represents a relatively inefficient use of the seaweed bioresource. These results should also apply to the use of other sources of seaweed biomass including those collected from the wild or as beach wrack; however, care must be taken when using these sources of biomass which typically have lower nitrogen contents (Lourenço et al. 2002) and will require a higher proportion of seaweed biomass to achieve the ideal initial C:N ratios of 22:1. It is inadvisable to compost seaweed biomass without knowing the carbon, nitrogen and C:N ratio of the individual feedstocks as without this information, the quality of the compost cannot be guaranteed and it represents an inefficient use of the seaweed resource. The high total nitrogen content of our seaweed-based composts and the positive effect these composts had on sugarcane growth demonstrates that seaweed composts can be used as an alternative source of nitrogen for the production of agricultural crops. However, the key outcome of this study is that by linking aquaculture and agricultural waste streams, we have demonstrated a simple integrated approach to recover and transform wastes into a useful input resource for the production of agricultural crops.

Acknowledgments This research is part of the MBD Energy Research and Development programme for Biological Carbon Capture and Storage. The project is supported by the Australian Renewable Energy Agency (ARENA) and the Advanced Manufacturing Cooperative Research Centre (AMCRC) funded through the Australian Government's Cooperative Research Centre Scheme. We thank Jonathon Moorhead, Tom Mannering, Lewis Anderson and Giovani Del Frari for assistance with experiments and the Burdekin Productivity Services for supplying the sugarcane stalks.

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