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Litterfall production and nutrient dynamics in mangrove systems on the Red Sea coast of Saudi Arabia

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Abstract. Litterfall production, decomposition and the release of chemical components were estimated in two Avicennia marina mangrove systems on the Red Sea coast, a northern site in Yanbu and a southern site in Shuaiba regions. Over a period of 2 years, monthly litterfall and litter standing stock production were estimated using litter traps and ground plots, respectively. The decomposition of leaf litter was assessed over a period of 256 days using litterbags, the changes in the chemical composition (carbon and nitrogen) and their ratios, and the chemical compound concentrations (leachable carbohydrates, cellulose, hemicelluloses and lignin) were estimated at each decomposition stage. The annual litterfall rates did not differ significantly between sites. In Shuaiba, monthly litterfall ranged from 87.7 kg ha-1 to 543.1 kg ha-1 with an annual litterfall rate of 3.68 t ha-1 y-1 while in Yanbu, the monthly litterfall ranged from 142 kg ha-1 to 539.5 kg ha-1 with an annual litterfall rate of 3.51 t ha-1. Monthly standing stock litter was significantly lower than monthly litterfall in both sites ($p < 0.05$) indicating litter removal from the forest floor, however, the removed litter is retained within the mangrove system rather than exported owing to low tidal ranges. The litterfall lost 41% of its mass in the first 64 days with no significant differences in final mass loss between Shuaiba and Yanbu sites ($p > 0.05$) and with a half-life value of approximately 90 days. The N concentration in the decomposing leaves was 40% lower than those of fresh leaves. In addition, the lignin concentration in litter increased over time and was negatively correlated to mass loss. These findings indicate low litter production and litter quality compared to systems in other parts of the world. Moreover, it indicates the accumulation and conservation mechanism of mangrove ecosystems in the extreme Red Sea environment.

Keywords: Avicennia marina; mangrove productivity; litterfall decomposition; nutrient cycling; Red Sea ecology

1. Introduction

Mangrove forests grow in tropical and subtropical zones on riverbanks and by seashores. Their unique presence at the boundaries of terrestrial and marine environments renders them an important ecological transition zone. The forest productivity supported by detritus food chains contribute to resident and migratory animals and birds and to the trophic balance in associated ecosystems (Lugo and Snedaker, 1974). Moreover, the litterfall via detritus pathways can be a significant source of energy to marine organisms existing in waters adjacent to mangrove habitat; litterfall can be directly used as feed for aquatic animals such as crabs, shrimps and small fish.

In Saudi Arabia, mangrove trees (*Avicennia marina* Forsk. Vierh.) are the dominant species on the Red Sea; they provide a remarkable visual and biological contrast to the comparatively barren terrain of surroundings desert. *Avicennia marina* grows widespread; however it generally forms a discontinuous and narrow belt fringing the shoreline of the Red Sea. These forests are interesting because they represent the only forest habitat in the coastal area of the country (Spalding *et al*., 1997). Mangroves of the region are well known to be the most tolerant plant to severe environmental conditions such as hyper water salinity, minimal fresh water input, extreme high temperature and hot and cold water exchange (Spalding *et al*., 1997). These forests are valuable and ecologically significant habitat with many uses to man. For example, mangrove leaves are used as fodder in aqua farming in the southern region of the Red Sea, and also as sole feed for desert camels (Almansi, 1999). The wood of *Avicennia marina* is also widely used for fuel (Chapman, 1976).

Information on the ecology of the Red Sea mangroves is limited; most previous research has been conducted on mangrove ecosystems on the coasts of Sinai where *Avicennia marina* growth is stunted and trees are smaller in number; they cling to a thin layer of soil barely covering coral rocks (Sheppard *et al*., 1992). Sheppard *et al*., (1992) gave an estimated figure of *Avicenna marina* gross productivity in Sinai Peninsula; they estimated mangrove's productivity to be 1690 kg O_2 d^{-1} with a relative productivity of 86% to other autotrophic communities (benthic macroalgae, microalgae and phytoplankton). However, no experimental measurements on trees and associated biota were done. For the rest of the Red Sea coast of Saudi Arabia, there have been only a few small scale productivity estimates (*i.e.* Khafaji *et al.*, 1991; Mandura, 1998 and Saifullah *et al.*, 1989). Edwards and Head (1987) hypothesized that mangrove stands in the Red Sea form a major source of high primary productivity in an otherwise barren zone. Moreover, they hypothesized that mangrove stands constitute a nutrient conserving and accumulating ecosystem as evidenced by the absence of nutrient inputs from rivers and oligotrophic waters of the Red Sea).

The objectives of this study were to estimate the annual litterfall production and decomposition in two mangrove stands on the Red Sea coast of Saudi Arabia In addition to investigate the effect of seasonal tidal levels on the removal and accumulation of litterfall on the forest floor.

2. Material and Methods

2.1 Site description

The study was conducted in two mangrove stands in Yanbu city in the northern Red Sea (24^o 02' 65" N and 38^o 09' 46"E) and in Shuaiba region in the southern Red Sea (20^{o}46' 2"N and 39^o 30' 21"E). Yanbu city is situated at the mouth of the Farah valley which forms one of the widest deltas along the Red Sea coast and contains the most extensive area of mangrove stands of *Avicennia marina* north of the Tropic of Cancer. Yanbu encompasses an area of approximately 185 km^2 in which mangrove trees cover an area of 0.9 km^2. Shuaiba is an old port laying at about 100 km south of the city of Jeddah, the region comprises two lagoons extending for some 20 km from north to south with the greatest width being 5 km, and each lagoon is connected to the sea through a small channel. Mangrove stands form a large basin population in the middle of the lagoons with an area of about 2 km^2.

The climate of the 2 sites is typical of the hot arid climate of the Red Sea with very few millimetres of rain annually. In Shuaiba temperature ranges from 18°C in February to 40°C in July with annual mean temperature of 29°C, the relative humidity is 58% and the mean annual precipitation is 15 mm. In Yanbu, the temperature ranges from 13°C in February to 41°C in August with an average annual temperature of 28°C. The mean annual precipitation is 10 mm and the relative humidity is 48%.

2.2 Sampling design

In Shuaiba, a trend in tree density, size and tree height was found; trees toward the eastern bank of the lagoon were bigger and denser than those toward the west. Based on these findings, four transects were set in north-south orientation perpendicular to the variation. In each transect, three permanent plots (50×50 m) were set at consistent distance along transects with a total of 12 plots. In Yanbu, it was found that trees were more homogenous in growth and density with no visual differences; therefore 12 plots (50×50 m) were randomly located on the site.

2.3 Litterfall production estimation

Litterfall production was estimated over a period of two years using the litter trap technique. One square meter traps with 4 mm^2 pore size was used. Five traps were randomly set in each plot and numbered with a total of 60 traps per site, and litterfall was collected monthly from each site.

Similarly, the standing crop of litter was collected to estimate ground leaf litterfall accumulation and removal. The experiment lasted a period of two years for both Yanbu and Shuaiba.

The standing crop estimation method involved collecting leaf litterfall from traps and ground plots at the same time, on the assumption that litter in ground plots were subjected to removal via water inundation. Therefore, the weight difference between leaf litter collected in traps (total litter) and ground leaf litter represent the amount removed from the forest floor per month (Robertson and Daniel, 1989, Twilley *et al.*, 1986).

This method encompasses the following assumption and considerations:

1. Ground plots have the same area (1 m^2) and placed in close proximity to the litter trap.

2. Ground litter is assumed to be solely removed by tidal activities.

3. The same amount of trap litter is assumed to fall on the corresponding ground plots owing to their proximity.

To set the ground plots, a 1 m^2 area was marked within the vicinity of the litter traps, cleared of aerial roots, debris, and other materials. A total of 18 ground plots per site were set for the standing crop experiment. Litterfall was collected monthly from traps and their corresponding ground plots, oven dried at 70°C for 24 hours and weighed.

2.4 Monitoring tidal activities

Tidal information for the Yanbu site was obtained from local tidal monitoring stations. In conjunction, *in situ* tidal measurements were made in both Shuaiba and Yanbu sites to provide a description of the local topography of the mangrove areas with respect to the obtained tidal levels. Marked wooden stakes were used as tidal indicators and placed in plots within each site. Water levels were recorded at each site and compared with the tabulated monthly tidal ranges (English *et al.*, 1997; LeVay, pers. comm., 2010).

2.5 Litter decomposition estimation

The litter decomposition experiment was done using the litterbag technique. In each site, senescent leaves were handpicked and air dried for a period of four hours; 30 g of litter were filled into 25 cm^2 mesh bags (1 mm mesh pore). The bags were sealed, secured in plots and sampled at nine sampling intervals (on days 1, 2, 4, 8, 16, 32, 64, 128 and 256). After placement, a total of 324 and 108 bags were used for the entire study in Shuaiba and Yanbu sites respectively; in Shuaiba, three bags were randomly sampled from each plot at each sampling interval, where in Yanbu, only one bag was sampled from each plot at each sampling interval. The initial litter dry weight (~26 g) was determined after calculating the moisture content of the senescent leaves.

The weight loss of the decomposing litter was expressed using exponential models; in Yanbu, the mass loss of litter was expressed using a single exponential model (Olson, 1963) following the equation:

$$y = W e^{-k_1 t}$$

Where y is the dry mass remaining at time t (days) and k is the decay constant.

While in Shuaiba, mass loss was expressed using a double exponential model (Wieder and Lang, 1982) following the equation:

$$y = W_1 e^{-k_1 t} + W_2 e^{-k_1 t}$$

Where y is the dry mass remaining at time t (days); k_1 and k_2 are decay constants for the labile and resistant components respectively, W_1 is the proportion of the labile fraction whilst W_2 is the proportion of the resistant plant material. However, when decay rates were compared to other published studies, the decay rates of single exponential models were used.

Half-life of leaf decomposition (time required for accumulated litter to lose half of their dry weight) was calculated following Olson (1963) as followed:

$$t_{(0.5)} = 0.693/k$$

Where $t_{(0.5)}$ is the time required for the material to lose half its weight, and k is the decay constant.

Leaf litter at different decomposition stages were analyzed for its chemical composition (C and N) and chemical compounds (leachable carbohydrates, hemicelluloses, cellulose and lignin) using subsamples from litterfall at each decomposition stage except for three which were mislaid (Day 16, Shuaiba; Day 256, both sites). For those, best fit prediction models were used to estimate missing values. Organic N and C content of leaf litter were analyzed using the combustion method (Carlo-Erba® NA 1500 analyzer, DEVIL, USA), while leachable substances, hemicelluloses, cellulose and lignin were analyzed following the methodology of Rowland and Roberts (1994) applied by the ANKOM technology method of fiber analysis (ANKOM, 2008a, b and c).

2.6 Chemical composition determination

Leaf litter at different decomposition periods was analyzed for its chemical composition (C and N) and chemical compounds (Leachable carbohydrates, hemicelluloses, cellulose and lignin), Subsamples from each decomposition period were used except for two which were mislaid (sample of Day 256, both sites), best fit prediction models were used to estimate these missing values. Organic N and C content of leaf litter were analyzed using the combustion method (Carlo-Erba® NA 1500 analyzer, DEVIL, USA), Subsamples (5 g) of ground, dried leaf litter were encapsulated in tin foil cones, placed in microplates, and analyzed in laboratory. Samples were combusted at 1020°C in the presence of chromium oxide and silvered cobaltic oxide catalysts to produce purified CO_2 and N_2 gases. While leachable substances, hemicelluloses, cellulose and lignin were analyzed following the methodology of Rowland and Roberts (1994) applied by the ANKOM technology method of fiber analysis (ANKOM, 2008a, b and c). Methods used to determine different litter parameters are as followed:

Chemical parameter	Method of determination
Carbon/Nitrogen	flash combustion technique (Carlo-Erba® NA 1500 analyzer, DEVIL, USA).
Hemicelluloses, Cellulose and Lignin	Neutral detergent fibre (NDF) using Filter bag technique (ANKOM^{2000}, 2008a).
Cellulose and Lignin	Acid detergent fibre (ADF) using Filter bag technique (ANKOM^{2000}, 2008b).
Lignin	Acid detergent lignin in beakers (ANKOM technology, 2008c).

2.6.1 Neutral detergent fiber (NDF) and Acid detergent fiber (ADF)

Nutrient detergent fibers are the residues remaining after digestion in a detergent solution, the resulting fibers residues are primarily hemicelluloses, cellulose and lignin. Three sealed filter bags (0.5 – 0.54 g) were weighed and used as blanks. Afterwards, 0.45-0.55 g of dried ground leaf samples were weighed in filter bags, labelled, and loaded into the analyzer machine. At the start of the NDF extraction, 20 g of Na_2SO_3 and 4 ml of alpha-amylase were manually added to digest the soluble (non-fiber) carbohydrates and a further 8 ml of alpha-amylase diluted in 350 ml of distilled water was added during the two following rinses. At the end of the NDF process, filter bags were removed, pressed to remove excess water, and covered with acetone in a beaker for five minutes. Afterwards, bags were removed from acetone and air dried on a wire screen before being oven dried at 102°C for four hours, filter bags were then reweighed on a digital scale. The %NDF was calculated from the equation:

$$\%NDF = \frac{[W3-(W1\,x\,C1)]}{W2}\,x100$$

Where:

W_1=Bag tare weight

W_2=Sample weight

W_3=Dried weight of bag with fiber after extraction process

C_1=Blank bag correction (Final oven dried weight divided by the original blank bag weight).

The acid detergent fibers are the residues remaining in the filter bags after digestion with

H_2SO_4 and Cetyl-trimethylammonium bromide (CTAB); the remaining residues are primarily celluloses and lignin. This method follows the same procedure as of the NDF however, no Na_2SO_3 and alpha-amylase is needed and the ADF solution is used. After the completion of the ADF process, the bags were similarly dried and %ADF was calculated using the same formula as for NDF.

2.6.2 Acid detergent lignin (ADL)

After the ADF determination, dried bags were covered with approximately 250 ml of 72% H_2SO_4 in a beaker and agitated every 30 minutes for a period of three hours. Afterwards, the H_2SO_4 was poured off and bags were rinsed with tap water until pH was neutral. Bags were then rinsed in acetone for about three minutes, air dried on a wire screen and later oven dried at 102°C for 4 hours; bags were then reweighed for lignin determination. Sample and blank bags were then ashed in a muffle furnace at 500°C for a period of 4 hours. Afterwards, the ash was cooled and weighed, the blank bags were used to obtain the bag ash correction using the weight loss on ignition. The %ADL was finally calculated from the equation:

$$ADL = \frac{[W4 - (W1xC2)]}{W2} x100$$

Where:

W_1=Bag tare weight

W_2= Sample weight

W_4= Weight of organic matter (loss of weight in ignition of bag and fiber residue)

C_2= Ash corrected blank bag (loss of weight on ignition of bag / original blank bag).

2.7 Statistical analysis

Data was analysed using SPSS (ver. 14) statistical package, differences in litterfall production and decomposition was tested using **o**ne-way ANOVA test (0.05 significance level)**,** differences in mean litter fall between sites was tested for significant using Student T-test; a pair-wise T-test was used to test for significant differences between litterfall and standing crop. Non-linear regression was used to find the best model fit, goodness of fit (r^2) and significance of fit (p) of the different decomposition models was explored via least squares regression estimate. Akaike Information Criterion (AIC) was further used to aid in best model selection (Burnham and Anderson, 1998). Principle components analysis (PCA) was employed to assess the relationships between the different chemical components and weight loss.

3. Results

3.1 Litterfall production

The annual litterfall rate in Shuiaba ranged from 80.4 kg ha^{-1} to 549.96 kg ha^{-1} with an overall annual litterfall rate of 3645 kg ha^{-1} y^{-1}, Generally, litterfall rates followed a bimodal annual cycle, high litterfall rates were significantly greater in summer months (March to July) than the rest of the year (p <0.05, Figure 1). The monthly standing stock leaf litter ranged from 18.85 kg ha^{-1} $month^{-1}$ to 440.55 kg ha^{-1} $month^{-1}$ with an overall annual production of 990.18 kg ha^{-1} y^{-1}, while trap leaf litter ranged from 15.98 to 532.61 kg ha^{-1} $month^{-1}$ with an overall annual litterfall of 2840.70 kg ha^{-1} y^{-1} significantly greater than ground litter (p <0.05) (Table 1a). In addition, significant differences between traps and ground litter were present during winter and spring months (January to June) in which the tidal ranges were highest of the year (Figure 2a). In Yanbu, the annual litterfall rates ranged from 128 kg ha^{-1} to 557 kg ha^{-1} (Figure 3) with an overall annual rate of 3509 kg ha^{-1} y^{-1} not significant different than Shuaiba annual litterfall production (Table 1b). The monthly standing stock litter ranged from 9.30 to 106.95 kg ha^{-1} month^{-1} with an overall annual rate of 494.73 kg ha^{-1} y^{-1}, while trap leaf litter ranged from 39.85 to 473.62 kg ha^{-1} month^{-1} with a mean rate of 169.21 kg ha^{-1} month^{-1} and an overall annual rate of 1861.36 y^{-1},

significantly greater than standing crop (*p* <0.05). Like Shuaiba, significant differences between litterfall and standing crop were present during winter months (high tide months) indicating litter removal from forest floor (Figure 2b).

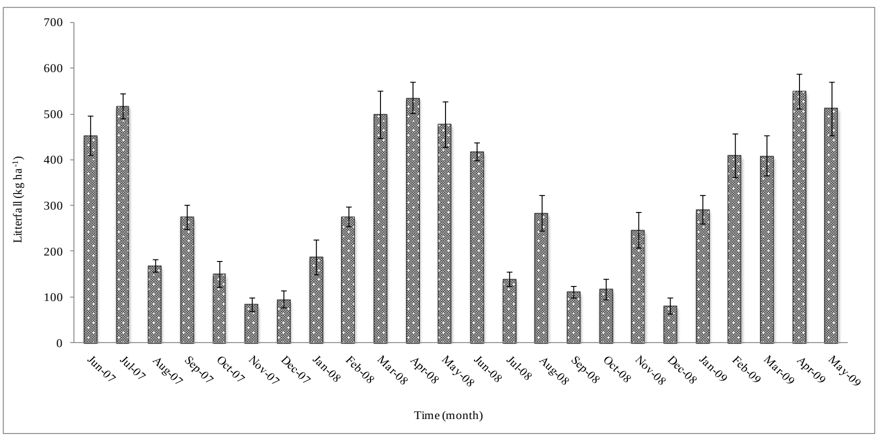

Figure 1. Mean monthly litterfall (kg ha^{-1}) for years (2007-2008) in a mangrove stand in Shuaiba site (error bars denote standard errors).

Table 1a. Annual litterfall and standing crop (kg ha^{-1} y^{-1}) in a mangrove stand in Shuaiba, Saudi Arabia

Leaf Litter	2007/2008	2008/2009	Overall
Litterfall (N=60)	2855.6	2825.8	2840.7
Standing crop (N=18)	1079.4	900.9	990.2

Table 1b. Annual litterfall rates (kg ha-1 y-1) in mangrove stands in Shuaiba and Yanbu, Saudi Arabia (± standard deviations)

Site	2007/2008	2008/2009	Overall
Shuaiba (N=60)	3720.6	3569.5	3645.1 ± 106.00
Yanbu (N=60)	3536.9	3512.9	3509.4 ± 38.81

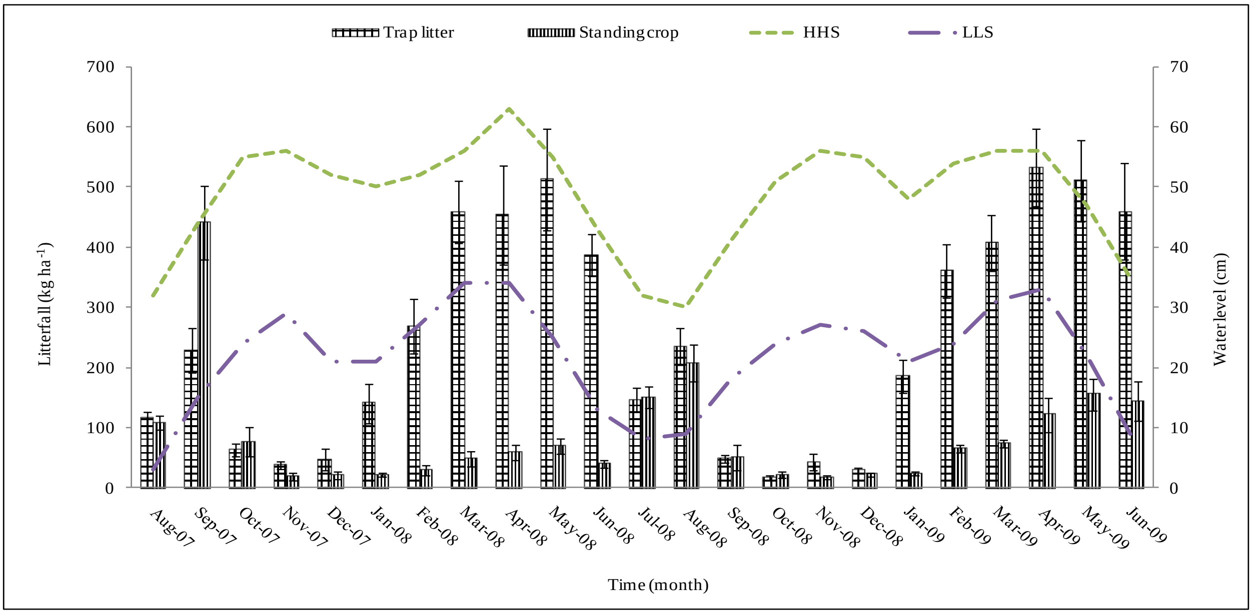

Figure 2a. Mean monthly litterfall and litter standing crop in a mangrove stand in Shuaiba site (HHS: highest high spring tide, LLS: lowest low spring tide, error bars are standard errors).

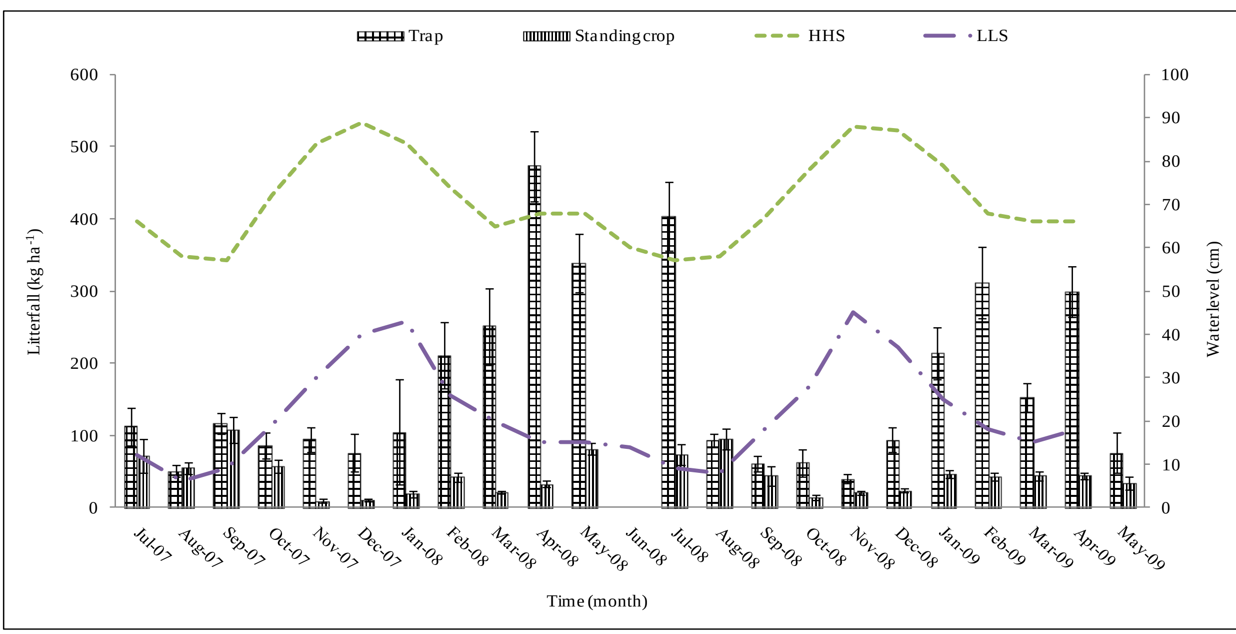

Figure 2b. Mean monthly litterfall and litter standing crop in a mangrove stand in Yanbu site (HHS: highest high spring tide, LLS: lowest low spring tide, error bards are standard errors).

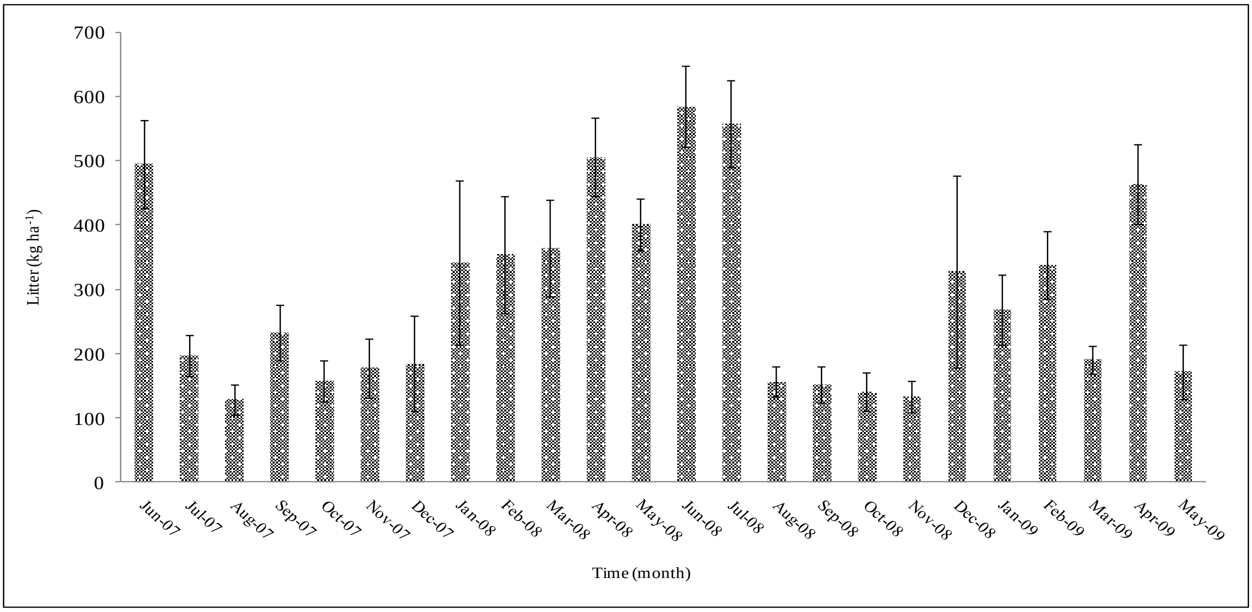

Figure 3. Mean monthly litterfall (kg ha^{-1}) for years (2007-2008) in a mangrove stand in Yanbu site (error bars denote standard errors).

3.2 Litterfall decomposition

At the end of the decomposition period (256 days), there were no significant differences in final mass between Shuaiba and Yanbu sites (p>0.05) (Figure 4) with only 7.5 and 11% of mass remaining for Shuaiba and Yanbu respectively. Shuaiba litter lost 52% of its original mass in the first 64 days, significantly greater than that of Yanbu (44%). In Shuaiba, a double exponential model best fitted the data (r^2 = 0.99). The relatively labile materials constituted a proportion of 36% of litter mass with a half-life of 2.5 days, the higher proportional mass (resistant materials) had a half-life of 94 days (Table 2). In Yanbu, the mass loss was consistent throughout the decomposition period and thus the single exponential model best describes the decomposition data (r^2 = 0.95).

Table 2. Parameters of double and single exponential models for leaf litter decomposition in the mangrove stands of Shuaiba and Yanbu sites respectively.

Parameter	Double exponential model	Parameter	Single exponential model
W_1 (%)	35.76	W (%)	95.93
k_1(day)	0.274 ± 0.17	k (day)	0.0076 ± 0.001
$t_{1(0.5)}$ (day)	2.53		
k_2 (day)	0.0074 ± 0.001	$t_{(0.5)}$ (day)	91
$t_{2(0.5)}$ (day)	94		
r^2	0.99	r^2	0.95
Adj r^2	0.98	Adj r^2	0.94
p	0.0002	p	< 0.0001

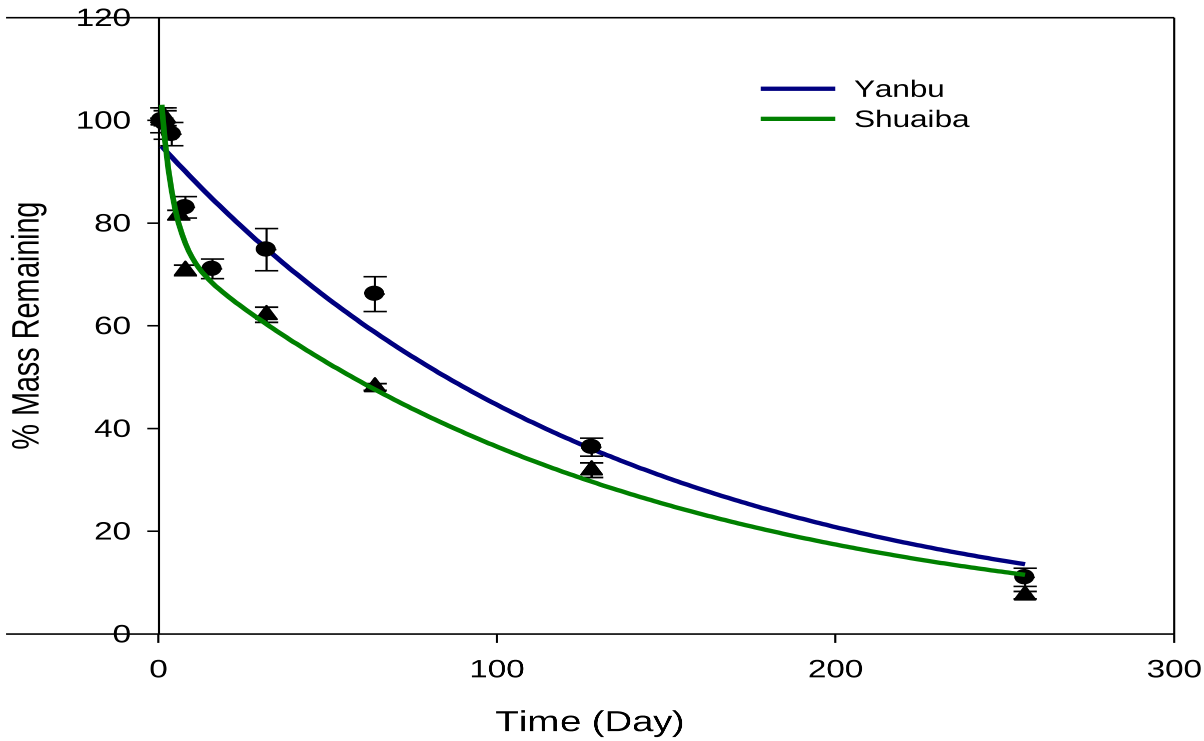

Figure 4. Changes of the remaining litter mass over the decomposition period (256 days) in a mangrove stand in Shuaiba (▲) and Yanbu (●), Saudi Arabia (error bars are standard deviations)

3.3 Changes in chemical composition

C and N concentration of the decomposing litter increased over time, C concentration appears to increase more at the later decomposition phase. For Shuaiba, C concentration ranged from 46.24 to 62.32 while in Yanbu, C concentration ranged from 46.01 to 56.10 with significant increase at the end of the decomposition period for both sites (p <0.05). The C concentration was predicted to reach 74.4 and 61.43 for Shuaiba and Yanbu sites respectively (Figure 4). Similarly, N concentration ranged from 0.48 to 1.21 and from 0.48 to 0.91 for Shuaiba and Yanbu respectively and N concentration significantly increased at the later phase of decomposition (p <0.05) (Figure 5). Furthermore, when N was determined in fresh and senescent leaves, it was found that both sites always had higher N concentration in fresh leaves than senescent (p < 0.05, Table 3), C:N ratios gave values that ranged from 96.64 to 63.44 and from 97.19 to 65.49 for Shuaiba and Yanbu respectively (p <0.05). C:N ratio declined consistently in both sites mainly as a result of the constant increase in N concentration over the decomposition period (Figure 6).

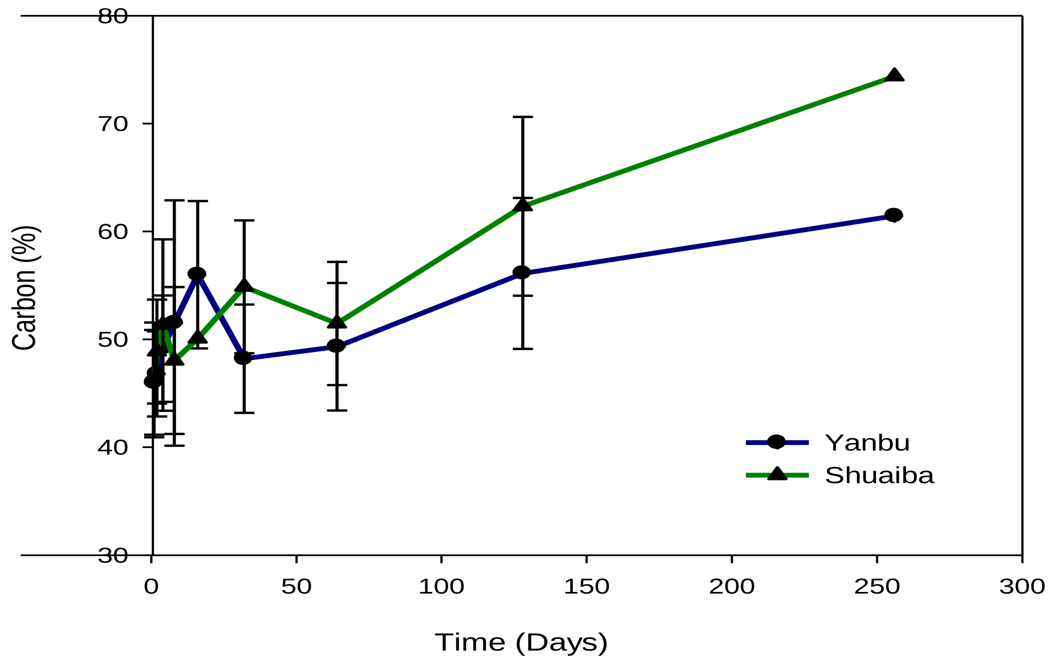

Figure 4. Carbon concentrations (%) of mangrove leaf litter over a 256 day decomposition period in mangrove stands in Shuaiba and Yanbu regions, Saudi Arabia (error bars are standard deviations).

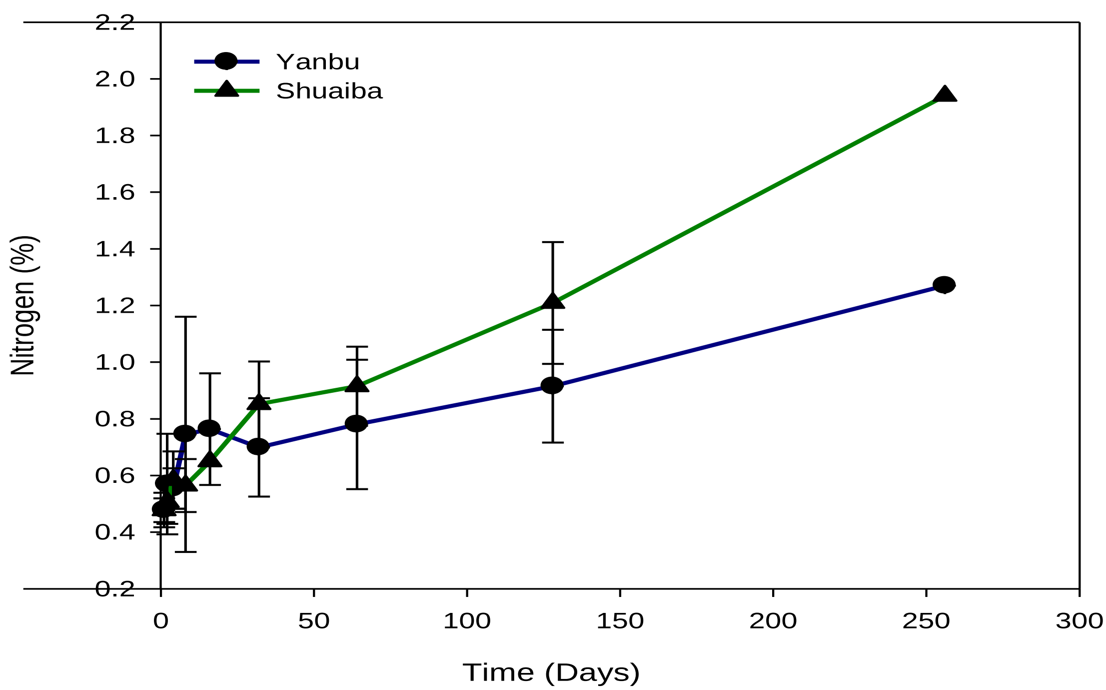

Figure 5. Nitrogen concentrations (%) of mangrove leaf litter over a 256 day decomposition period in mangrove stands in Shuaiba and Yanbu regions, Saudi Arabia (error bars are standard deviations).

Table 3. Nitrogen concentrations in fresh and senescent leaves (N=12) in mangrove stands in Shuaiba and Yanbu regions, Saudi Arabia

Site	Fresh leaves	Senescent leaves	Resorption (%)
Shuaiba	1.19 ± 0.54	0.49 ± 0.01	59
Yanbu	1.34 ± 0.37	0.54 ± 0.05	60

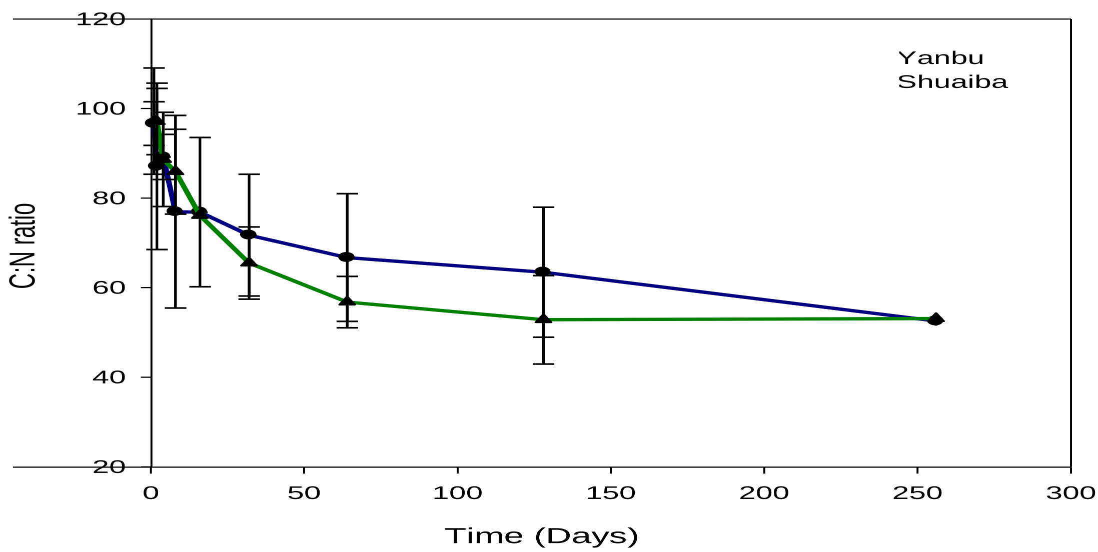

Figure 6. C:N ratios of mangrove leaf litter over a 256 day decomposition period in mangrove stands in Shuaiba (▲) and Yanbu (●) regions, Saudi Arabia.

The analysis of the chemical components of the decomposing litter showed similar trends between both sites, although initially, Shuaiba had 46% of the soluble carbohydrates leached from litter after one month of decomposition compared to 14% being lost in Yanbu. However, by the end of the decomposition period, the sites did not significantly differ in the final soluble carbohydrates concentration (p >0.05). Hemicelluloses decay appeared constant through the decomposition period with no declining pattern, values ranging from 9.09 to 15.19 in Shuaiba and from 8.44 to 16.64 in Yanbu and predicted to continue with the same pattern until day 256 (Figure 7 and 8).

Cellulose concentration in Shuaiba was found to decline significantly (from day 8 onwards, p<0.05) contrasting with the increase of lignin concentration. In Yanbu, cellulose was also found to follow a similar trend contrasting with lignin, increasing to day 16, decreasing afterwards before increasing again at the end of the decomposition period. The ratio of lignin to lignin and cellulose (lignified cellulose index, LCI) was used to examine the relative increase in lignin to cellulose (or the change of litter susceptibility to microbial decay). In Shuaiba, it was found that by the end of the decomposition period, LCI significantly increased from 0.63 to 0.88 (p<0.05), while in

Yanbu, there was no significant increase in LCI overtime (Table 4).

Lignin concentration significantly increased over the decomposition period rising from 23.07 to 44.30 in Shuaiba and from 18.5 to 34.09 in Yanbu (p<0.05). Lignin concentrations in Shuaiba leaf litter were generally higher than those in Yanbu and found to be significantly higher at the end of decomposition period (44.3 vs. 34.09) for Shuaiba and Yanbu respectively (p<0.05). Furthermore, the increase in lignin concentration reached its maximum at day 128 in both sites with no expected increase at day 256 (Figure 7 and 8).

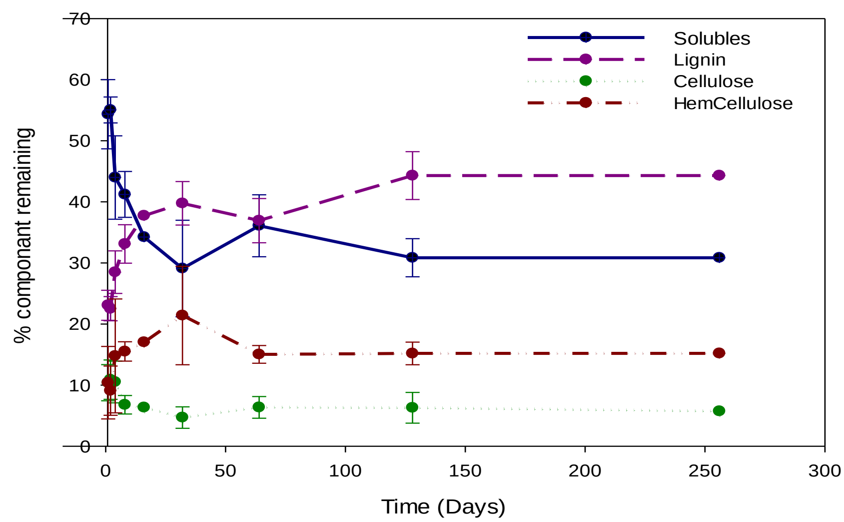

Figure 7. Mass remaining of the different chemical components in a mangrove stand in Shuaiba, Saudi Arabia.

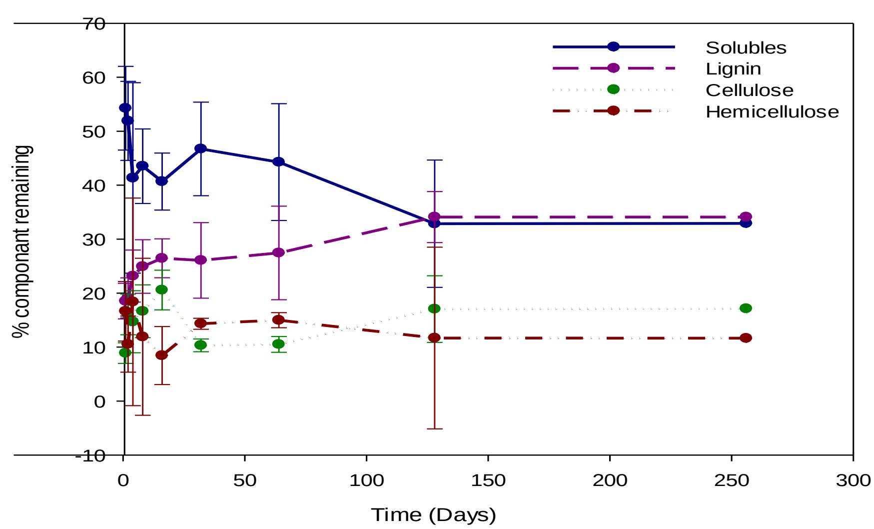

Figure 8. Mass remaining of the different chemical components in a mangrove stand in Yanbu, Saudi Arabia.

Principle component analysis (PCA) was employed to explore the relationships between mass loss and the different chemical components, C:N, and LCI ratios. In Shuaiba, 78% of the total variance was explained by the first 2 vectors with PCA1 and PCA2 explaining 57 and 21% of total variance respectively (Table 4). In addition, the correlation matrix of PCA analysis showed that mass loss was strongly correlated to lignin (r = -0.85), nitrogen (r = -0.75) and C:N ratio (r = 0.81) at p <0.001. As mass loss decreased during decomposition the proportion of lignin and N increases while the C:N ratio decreases (Figure 9). Similar to Shuaiba, the total mass loss in Yanbu site was highly correlated to lignin increase (r = -0.74, p<0.001).

Table 4. Total variance explained by the different PCA components

Component	Initial Eigen values		
	Total	% of Variance	Cumulative %
1	5.180	57.55	57.55
2	1.863	20.70	78.26
3	0.715	7.950	86.21
4	0.634	7.046	93.25

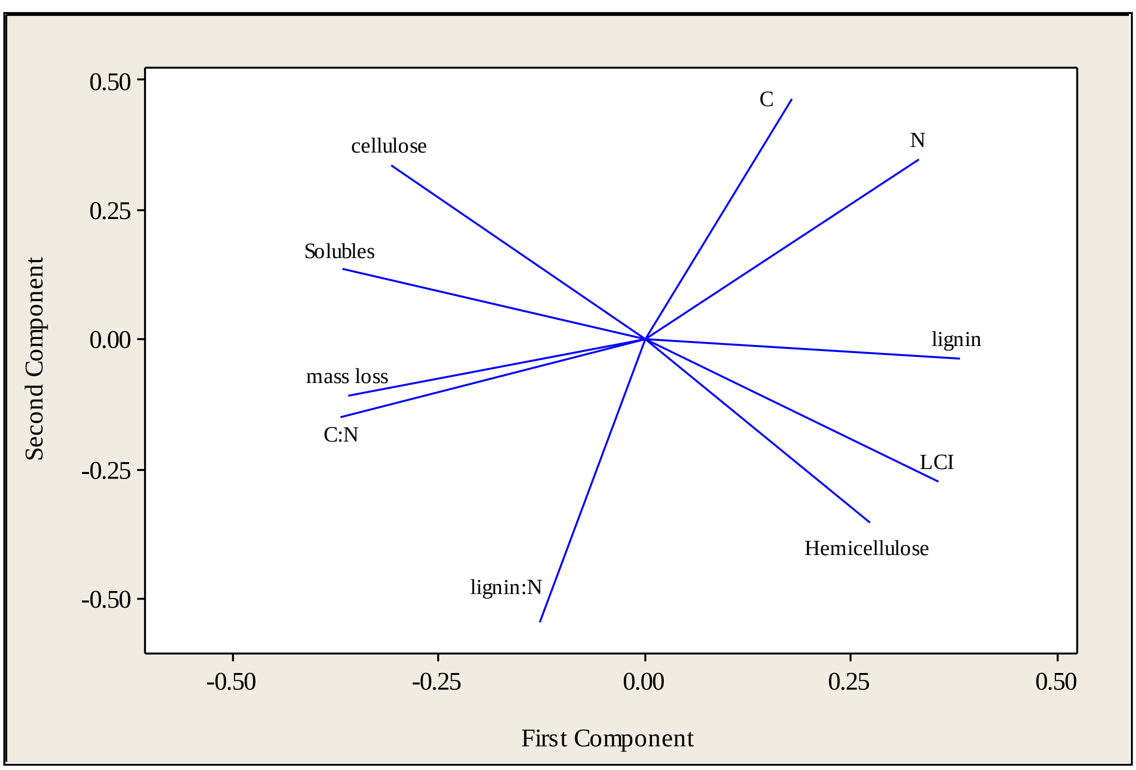

Figure 1: PCA analysis of Shuaiba mass, carbon and nitrogen losses with the different chemical compounds.

4. Discussion

4.1 Litterfall production

Generally, litterfall rates were always higher in summer than in winter, this seasonal variation was clearer in Shuaiba than in Yanbu. Seasonality in litterfall rates is commonly reported in the litterature of mangrove litterfall on the Saudi Arabian Red Sea coast (*e.g.* Saifullah *et al.*, 1989; Mufti, 1990; Khafaji, *et al.*, 1991; Mandura, 1998) and in other mangrove systems around the world (*e.g.* Schories *et al.*, 2003, and Bosire *et al.*, 2005). Seasonality is attributed to a number of factors including precipitation, relative humidity, wind activity, freshwater discharge, salinity, frequency of tidal flushing and air temperature. Summer is characterised by high temperature, high solar radiation and by the lowest tidal amplitude, these factors can increase drought and soil salinity. In addition, low frequency of tidal flushing will minimize root oxygenation as well as washing excess salt and toxic sulphide from the top soil. In response to such stressful condition, the plant tends to spend extra energy to maintain the green photosynthetic leaves and shed senescent leaves (Amarasinghe and Balasubramaniam, 1992). The Red Sea is considered one of the most saline water bodies in the world with salinity levels reaching 40%, this has a direct effect on the biota in intertidal and subtidal regions, and when accompanied by high evaporation and low tidal inundation in summer can result in hypersalinity (up to 300%) in coastal lagoons and low water interchange areas. Low water inundation can affect inshore oxygenation and results in complete oxygen depletion during summer (Edwards and Head, 1987).

Litterfall estimates of the current study were less than estimates of similar locations on the Red Sea. Both Shuaiba and Yanbu sites had litterfall estimates that were 34% less than those reported by Mandura (1998) of 5.44 t ha^{-1} and 58% less than those reported by Saifullah *et al.* (1989) of 8.34 t ha^{-1}, in central Red Sea region. The reported high estimate by Khafaji *et al.*, (1991) of 8.62 t ha^{-1} in southern Red Sea is not surprising; mangroves of the region are well developed, growing under much favourable climates. Compared to the central and northern regions, mangroves of the southern region receive sufficient nutrient and freshwater via higher tidal ranges carrying nutrient rich water and through terrestrial runoffs, thus productivity is higher (Sheppard *et al.*, 1992). In addition, considering the time span between the previous and current estimates (10 to 19 years), the obtained results can indicate an overall production deterioration of the mangroves due to several reasons including increase in the overall temperature, salinity levels, low rainfall, exploitation (*i.e.* fuel wood and over grazing), urbanization, and pollution.

Avicennia marina litterfall production of the Red Sea mangroves were similar to reported estimates in extreme environments, the litterfall rate of the current study was 3.57 t ha^{-1} close to those reported in Sri Lanka by Amarasinghe and Balasubraminiam (1992) of 3.64 and those reported in Australia by Clough and Attiwill (1982) of 2.0 t ha^{-1}. The highest litterfall estimates came from the tropics (Woodroffe *et al.*,1988) of 12.5 and (Sasekumar and Loi 1983) of 15.4 t ha^{-1} where mangroves flourish.

The monthly standing stock litter was lower than the trap litter; this difference was obvious in seasons with high tidal levels. The removal of litter from the forest floor can be largely attributed to tidal activities (Hogarth, 2007). Although tidal levels removed litter from the forest floor, it is not expected that much of the litter would be exported from the mangroves owing to the low tidal ranges. The highest high tide reached only 63 and 88 cm for Shuaiba and Yanbu respectively, high enough to probably only move and "relocate" litter on the forest floor rather than export outside the stand.

4.2 Litterfall decomposition

Differences in decay rates of mangrove litter are generally attributed to species type and their litter initial chemical contents (Robertson and Alongi, 1992, Alongi *et al.,* 2000), local environment (*i.e*. temperature, soil aeration, tidal inundation, salinity, and animal consumption) (Lee, 1999, Dick and Osunkoya, 2000), and geographical location (Tam *et al.*, 1998). The current investigation showed that with respect to local environment and geographical region, litter decomposition rates in Shuaiba and Yanbu are similar due to the similarity in climatic and environmental conditions.

Avicennia marina decay constants of the current study were similar to those obtained in similar environments; in general, decay rates were low in arid and semi arid regions with half-life varying from 70 to 91 days. High solar radiation (Austin and Vivanco, 2006), low precipitation and tidal inundation (Dick and Osunkoya, 2000) are factors that slow decay rates; frequently inundated leaves have higher decay rates than dry or less inundated leaves as moisture promotes leaching and provide a favourable and more stable media for microorganism activity and production (Robertson and Alongi, 1992; Tam *et al*., 1990).

4.3 Changes in chemical composition

Nitrogen is generally a scarce nutrient in mangrove ecosystems. The N enrichment in the decomposing litter is frequently reported in literature (Mfilinge *et al.,* 2002, Zhou *et al*., 2010, and Nordhaus *et al.*, 2011). Alongi *et al.*, (1992) working on Bruguiera gymnorrhiza and *Kandelia candel* mangroves reported that low initial N levels in Bruguiera gymnorrhiza litter were associated with N immobilization while the N enriched *Kandelia candel* favoured N mineralization. The N immobilization of the decomposing litter might be due to incorporation into microbial biomass, and the production of microbial activities such as phenols, small peptides, and amino acids (Fell and Masters, 1980; Rice 1982; Rice and Hanson, 1984; Camilleri and Ribi, 1986). In addition, microbial N immobilization can be a conservation strategy in such nutrient poor environment which results in the further decrease of the C:N ratio (Ochieng and Erftemeijer, 2002). The senescent leaves had 60% less N concentration compared to the fresh leaves indicating nutrient resorption prior to leaf senescence, this agrees with Woodroffe *et al.,* (1988) reporting N resorption in *A. marina* by 60%, and Ocheing and Erftemeijer (2002) who reported resorption of *A. marina* N of up to 68%. Mangrove species are known to be efficient in retaining and recycling nutrients as a conserving strategy (Alongi *et al.*, 1992) and with the minimal nutrient in welling in the Red Sea, the availability of N through the process of decomposition, mineralization and incorporation of organic matter into sediment becomes important, as retaining and recycling are probably the only source of nutrients in such ecosystem (Edwards and Head, 1987). By doing so, mangroves are able to use the same unit of nutrient to build new leaves and other plant components.

Carbon is an element that is present in both soluble and structural carbohydrates; the relatively unchanged C concentration in Shuaiba litter could be related to the increase in lignin concentration relative to the loss of soluble carbohydrates. The significant increase of C at the end phase of decomposition corresponds with the maximum increase of lignin concentration. This suggests that C enters humic matter in the form of lignin rather than cellulose. Moreover, the significant increase in the LCI values from initial 0.69 to final 0.88 supporting this assumption and indicating that lignin is the dominant component at later stages of decomposition. Mfilinge *et al.*, (2002) obtained similar C increases attributed to increased lignin concentrations. In Yanbu litter, a steady C concentration seems to be balanced between cellulose and lignin, and C entering soil seems to be in both lignin and cellulose forms. The C:N ratios of *A. marina* were generally higher than those reported in other environments due mainly to low litter N content and resorption level affected by low nutrient input and by N deficiency. High C:N ratio even after 256 days of decomposition, associated with high lignin concentration, lower the quality of litter and therefore slowed down litter mass loss. As a result, the resistant litter is accumulated on the forest floor forming few centimetres of peat. Generally, leaves with C:N ratio below 25 and lignin content below 15% are considered high quality (Palm and Sanchez, 1990). Lignin is found to be the best indicator for mass loss and constitutes the major source of C entering mangrove soils; it is thought that lignin-source C utilization for microbial biomass is low, with most C is released as CO_2 or incorporated into soil humus (Sylvia *et al.*, 1999); Moreover, lignin is a large complex polymer that only minimal groups of microorganisms able to degrade and therefore, the high concentration of lignin in *A. marina* leaves probably prolonged half-life decay of the litter as the number of microorganisms capable of decaying lignin is minimal.

5. Conclusion

With respect to the global estimates of annual litterfall production for mangrove ecosystems, productivity of the Red Sea *A. marina* mangrove trees are among the lowest of global estimates. A reduction in the annual litterfall production compared to previous estimates on the Red Sea coast indicates productivity deterioration and thus suggests management and conservation programs. The litterfall produced is retained in the mangrove system rather than exported due to the low tidal levels resulting in only relocation of the litter on the forest floor. The decomposition of the litter is low owing to low litter quality. Changes in the C:N ratio and lignin concentration can be indicative of mass loss, and high lignin content and C:N ratio resulted in slow decomposition. Moreover, mangrove trees tend to retain much of the N in leaves prior to abscission contributing to high C:N ratios in litter.

These finding support the nutrient conservation and recycling theories suggested for the Red Sea mangroves. However, such conditions may not be the same in other parts of the Red Sea. *Avicennia marina* flourishes in the southern region of the Red Sea and coexists with *Rhizophora mucronata* in a favourable local environment (*i.e.* milder temperature, nutrient and fresh water inwelling) which might greatly influence nutrient cycling. It would be of great interest to investigate the mass loss and litter quality of *A. marina* in such environmental conditions, and between the coexisting *A. marina* and *R. mucronata* of the southern region of the Red Sea coast, such investigations would provide a clear picture of litterfall production and nutrient dynamics in different mangrove ecosystems on the Red Sea coast.

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إنتاجية الطرح الخضري وحركة العناصر الغذائية في نظم المانجروف على ساحل البحر الأحمر للمملكة العربية السعودية

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المستخلص. تم تقدير إنتاجية وتحلل الطرح الخضري وتحرر المركبات الكيميائية في نظامين من أشجار القرم (Avicennia marina) على ساحل البحر الأحمر، موقع شمالي في مدينة ينبع وموقع جنوبي في منطقة الشعيبة وذلك على مدى عامين، تم تقدير الإنتاج الشهري للطرح الخضري باستخدام المصائد المعلقة ومخزون الطرح الدائم باستخدام المرابيع الارضية. تم تقييم تحلل الطرح الورقي على مدى ٢٥٦ يومًا باستخدام أكياس التحلل، وتم تقدير التغيرات في التركيب الكيميائي (الكربون والنيتروجين) ونسبها وتركيزات المركب الكيميائي (الكربوهيدرات القابلة للترشيح، السليلوز، الهيميسليلوز واللجنين) في كل مرحلة من مراحل التحلل. لم تختلف معدلات الطرح السنوية بشكل كبير بين المواقع. في الشعيبة، تراوحت تقديرات الطرح الشهرية من ٨٧,٧ كجم للهكتار إلى ٥٤٣,١ كجم للهكتار بمعدل سنوي قدره ٣,٦٨ طن للهكتار في السنة، اما في ينبع ، تراوحت تقديرات الطرح الشهرية من ١٤٢ كجم للهكتار إلى ٥٣٩,٥ كجم للهكتار بمعدل سنوي قدره ٣,٥١ طن للهكتار. كان مخزون الطرح الشهري أقل بكثير من الطرح الشهري في كلا الموقعين ($p<0.05$)مما يشير إلى إزاحة الطرح من أرضية الغابة، ومع ذلك يتم الاحتفاظ بالطرح الذي تمت إزاحته داخل نظام القرم بدلاً من تصديرها الى خارج النظام وذلك بسبب نطاقات المد والجزر المنخفضة. فقدت أوراق الطرح الخضري ٤١٪ من كتلتها في أول ٦٤ يومًا مع عدم وجود فروق معنوية في الفقد النهائي بين موقعي الشعيبة وينبع ($p> 0.05$) وكانت قيمة نصف العمر للأوراق تقارب ٩٠ يومًا. كان تركيز النيتروجين في الأوراق المتحللة أقل بنسبة ٤٠٪ من تركيز الأوراق الحديثة. بالإضافة إلى ذلك، زاد تركيز اللجنين في الطرح بمرور الوقت وكان مرتبطًا عكسيا بفقدان الكتلة. تشير هذه النتائج إلى انخفاض إنتاج الطرح الخضري وجودته مقارنة بالأنظمة في أجزاء أخرى من العالم. علاوة على ذلك، فإنه يشير إلى آلية التراكم والاحتفاظ بالمغذيات في النظم البيئية لأشجار القرم في بيئة البحر الأحمر الصعبة.