Sediment properties and CO_2 efflux from intact and cleared temperate mangrove forests

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8   **Abstract**

9   Temperate mangrove forests in New Zealand have been increasing in area in recent decades.

10   Recreational and amenity values or perceived loss of other estuarine habitats due to

11   expanding temperate mangrove forests have resulted in clearing of temperate mangroves. In

12   this study, we investigated the impact of temperate mangrove clearance on sediment CO_2

13   efflux and associated biotic and abiotic factors. This is the first study to investigate the effect

14   of clearing on sediment CO_2 efflux in temperate *Avicennia marina* forests.

15   Sediment CO_2 efflux rates in intact (1.95 ± 0.53 µmol m^{-2} s^{-1}) and cleared (1.55 ± 0.43 µmol

16   m^{-2} s^{-1}) mangrove forests did not differ significantly (1.55 ± 0.43 µmol m^{-2} s^{-1}) did not differ

17   significantly, and showed high between-site variability. Pre-shading the sediment for > 30

18   minutes prior to dark CO_2 efflux measurements was found to have no significant effect on

19   sediment CO_2 efflux. Mangrove above ground biomass, chlorophyll α concentration and

20   sediment temperature were the main factors explaining the variability in sediment CO_2 efflux

21   in intact mangrove forests. In contrast, sediment organic carbon and nitrogen concentration

22   and sediment grain size were the main factors explaining the variability in sediment CO_2

23   efflux in cleared mangrove sites. Our results show that sediment CO_2 efflux from intact and

24   cleared temperate mangrove forest is comparable to rates measured in tropical mangrove

25   forests.

26

1. Introduction

Mangrove forests are generally confined to the tropics, between latitudes 30°N and 30°S. However, approximately 1.4% of the global mangrove forests are located outside this latitudinal range, growing in conditions which may be broadly characterised as temperate (Morrisey et al., 2010). Temperate mangrove forests mainly occur in Australia, New Zealand, the United States of America and South Africa (Morrisey et al., 2010; Giri et al., 2011). Temperate mangrove forests are subject to colder and generally more variable climatic conditions, and are typically associated with lower diversity of tree species and lower faunal abundance and diversity than in the tropics (Alfaro, 2006; Morrisey et al., 2010). To date, little is known of the biogeochemical processes in temperate mangroves (Livesley and Andrusiak, 2012).

Temperate mangrove forest coverage has increased significantly over the last 50-60 years (Morrisey et al., 2010; Saintilan et al., 2014). A landward expansion of mangroves into salt marsh is observed in Australia and USA (Cavanaugh et al., 2014; Saintilan et al., 2014) while mangrove expansion into tidal flats is typically observed in New Zealand (Stokes et al., 2009; Lundquist et al., 2014a). In addition, there is evidence of mangrove expansion from tropical areas northwards and southwards to temperate regions (Saintilan et al., 2014). The expansion of mangroves in New Zealand has been linked to increased sedimentation leading to vertical accretion of tidal flats (Swales et al., 2007; Stokes, 2010), increased nutrient inputs (Saintilan and Williams, 1999), and climatic factors (Burns and Ogden, 1985; Lovelock et al., 2010).

The recent expansion of mangrove has led to a push towards mangrove removal in New Zealand, largely from local communities concerned about the loss of diversity of estuarine habitats, or for human amenities such as recreational access and water views (Harty, 2009). Numerous legal and illegal clearings have occurred in recent decades, ranging in scale from small < 0.1 ha clearings to clearances exceeding 100 ha (Morrisey et al., 2010; Lundquist et al., 2014a).

Carbon (C) cycling and storage are important ecosystem services provided by mangrove forests (Twilley et al., 1992; Bouillon et al., 2008; Kristensen et al., 2008; Alongi, 2014). Global net primary productivity in mangrove forest has been estimated at 218 ± 72 Tg C a^{-1}, which includes the rate of litterfall, above- and below-ground biomass production (Bouillon et al., 2008). An important component of the carbon cycle is the efflux of carbon dioxide (CO_2) from the sediment into the atmosphere (Raich and Schlesinger, 1992). Sediment CO_2

59   efflux (also called soil/sediment respiration) is the total of CO_2 released through

60   root/mycorrhizae respiration (autotrophic respiration) and microbial respiration

61   (heterotrophic respiration) associated with the decomposition of organic matter (Bouillon et

62   al., 2008).

63   Clearing will have an impact on the tree and sediment carbon storage and fluxes (Lovelock et

64   al., 2011; Sidik and Lovelock, 2013; Lang'at et al., 2014). For example, the accumulation of

65   mangrove-derived carbon from living mangrove into the sediment is halted following

66   mangrove clearance, yet the release of CO_2 from the sediment continues (Lovelock et al.,

67   2011; Sidik and Lovelock, 2013). The rates of sediment CO_2 efflux from cleared tropical

68   mangrove peat forest have been shown to be significantly higher compared to intact

69   mangrove forests (Lovelock et al., 2011). However, the impact of clearance on sediment

70   carbon storage and sediment CO_2 efflux has not been investigated in temperate mangrove.

71   Quantifying sources of carbon has become increasingly important due to the rapid rise in

72   atmospheric CO_2 concentrations and associated impact on global climate (IPCC, 2013).

73   Studies from tropical mangrove forests have shown that sediment CO_2 efflux is influenced by

74   sediment carbon and nutrient quantity (Chen et al., 2010; Chen et al., 2012; Leopold et al.,

75   2013; Chen et al., 2014) and quality (Kristensen, 2000), sediment grain size (Chen et al.,

76   2010), sediment water content (Alongi, 2009), redox potential (Chen et al., 2010; Chen et al.,

77   2012; Leopold et al., 2013) and sediment temperature (Chen et al., 2012). Conducting

78   measurements in temperature and tropical mangroves, Lovelock (2008) found a positive

79   correlation between leaf area index and sediment CO_2 efflux. Further, sediment microbial

80   communities present on the sediment surface, also called biofilm communities, comprised of

81   cyanobacteria, diatoms, and other microalgae, may also play an important role in mediating

82   CO_2 exchange from the sediment (Alongi et al., 2012; Leopold et al., 2013; Leopold et al.,

83   2015). However, the relative contribution of abiotic and biotic factors on sediment CO_2 efflux

84   from cleared temperature mangrove forest remains to be tested.

85   The aim of this study was to assess the effect of temperate mangrove forest clearance on

86   sediment CO_2 efflux and sediment characteristics. The specific objectives were to quantify

87   the sediment CO_2 efflux from intact and cleared mangrove forest and to investigate the

88   relationship between abiotic and biotic factors and sediment CO_2 efflux. The effect of pre-

89   shading the sediment prior to dark chamber measurements was also investigated. This was

90   due to the observation of CO_2 uptake during dark chamber measurements. The uptake might

91   be attributed to the continuation of photosynthetic activity by surface biofilm communities at

92   the onset of dark measurements until coenzymes were depleted (NADPH, ATP) (Leopold et
93   al. (2015).

2. Materials and methods

2.1 Study species

96   The only mangrove species in New Zealand, *Avicennia marina* subsp. *australasica* occurs
97   from the top to the central North Island (Morrisey et al., 2010). The southernmost limit (38º)
98   is most likely due to low temperatures (Duke, 1990), lack of suitable conditions for propagule
99   dispersal, and lack of suitable habitat (Lange and Lange, 1994). The height of mature
100   mangrove trees in New Zealand range from less than 1 m to over 6 m, with smaller trees
101   often occurring towards the southern range limit (Morrisey et al., 2010).

2.2 Study area and selection of study sites

103   This study was conducted at 23 sites covering a large proportion of the geographic range of
104   mangroves (35º43' S to 37º 41' S) in New Zealand (Figure 1). We investigated cleared (n =
105   23) and, where possible, adjacent intact mangrove forest sites (n = 13). The time since
106   mangrove removal ranged from 1 month to over 8 years. Cleared mangrove sites ranged in
107   area from < 0.1 ha to > 13 ha. Besides the difference in time since clearing and area of the
108   clearing the sites differed in shape, hydrodynamic exposure, and method of clearance
109   (Supplementary table 1). Mean air temperature ranges from 19ºC during summer to 11ºC
110   during winter. Mean monthly rainfall varies from 77 to 152 mm, respectively (NIWA, 2014).
111   Tides for the sites are semi diurnal with a range of 1.3 – 4.1 m (LINZ, 2014).

112   Field measurements and sampling were undertaken during late spring and summer
113   (November 2013 - January 2014). Weather conditions during sampling were sunny or
114   overcast, with no rainfall. Additional measurements were undertaken during winter (May-
115   June 2015) within intact mangrove forest at one site (Hatea 1) (Figure 1).

2.3 Sediment CO_2 efflux measurements

2.3.1 Shading experiment

118   Frames (0.5 m^2) were located approximately 20 cm above the sediment surface at Hatea 1.
119   The frame was completely covered by layered cloth to exclude light penetration. Three
120   frames were deployed throughout the mangrove forest, at least 10 m from each other and the
121   mangrove edge. After 30 minutes of shading, two CO_2 efflux measurements using a dark
122   respiration chamber were conducted at different locations within the 0.5 m^2 area, before and

5

123 after the removal of the surface biofilm. The biofilm (top ~2 mm of surface sediment) was

124 scraped off using a spatula. Biofilm removed measurements were conducted immediately

125 following biofilm intact measurements at the same location. Corresponding dark CO_2 efflux

126 measurements were also conducted at locations that had not been pre-shaded (control)

127 adjacent to each shaded measurement, as well as corresponding biofilm removed

128 measurements to account for heterogeneity in sediment conditions.

129 *2.3.2 Sediment CO_2 efflux from intact and cleared temperate mangrove*

130 Sediment CO_2 efflux was measured in the centre of the cleared sites at three randomly

131 selected locations. Locations in the intact mangrove forest were > 10 m from the cleared

132 areas. No pre-shading of the sediment was undertaken prior to measurements.

133 The sediment CO_2 efflux was measured at low tide, between 8 am and 6 pm local time, using

134 an infrared CO_2 analyser (Environmental Gas Monitor (EGM-4) with a dark sediment

135 respiration chamber (SRC-1, PP Systems Ltd., Amesbury, MA, USA). Using a dark chamber

136 prevents the photosynthetic activity of benthic microbial communities which results in the

137 uptake of CO_2. A PVC collar (10 cm height) was attached to the base of the respiration

138 chamber to protect the chamber from potential flooding. The collar was inserted

139 approximately 5 mm into the sediment, avoiding damage to surface roots. Sediment within

140 the chamber included crab burrows and pneumatophores < 7 cm which fit within the

141 respiration chamber. The sediment area covered by each chamber was 0.00785 m^2. Chamber

142 height was measured during each measurement as collar insertion varied based on sediment

143 characteristics. Total chamber volume varied between 1.72 and 1.98 l depending on the depth

144 of collar insertion. The CO_2 concentration in the chamber was measured at 5 second intervals

145 over a 90 second period. Air and sediment temperature (Novel Ways temperature probe) and

146 moisture (CS620, Campbell Scientific, Logan, UT, USA) to a depth of 12 cm was measured

147 with each CO_2 efflux measurement.

148 In addition to measuring CO_2 efflux in intact (undisturbed) sediment, sediment CO_2 efflux

149 was re-measured at the same location after the removal of the surface biofilm. Measurements

150 were made within 30 seconds following the removal of the surface biofilm.

151 The sediment CO_2 efflux rate was calculated as follows.

152 $$CO_2 \text{ flux } (\mu mol\ m^{-2}\ s^{-1}) = (\Delta CO_2/\Delta t) \text{ x } (P \text{ x } V/R \text{ x } T \text{ x } A) \tag{1}$$

153 Where $\Delta CO_2/\Delta t$ is the change in CO_2 concentration over time, based on the slope of the linear

154 regression ($\mu mol\ mol^{-1}$), t is time (s), P is the atmospheric pressure (Pa), V is the volume of

155   the chamber including collar (m^3), A is the surface area covered by each chamber (0.007854

156   m^2), T is the temperature (K), R is the ideal gas constant, 8.20528 m^3 PaK^{-1} mol^{-1}).

157   Sediment CO_2 efflux was only calculated if the linear regression of CO_2 concentration vs.

158   time had r^2 values ≥ 0.8.

2.4 Sediment characteristics

160   At each site three sediment samples, next to the location of the sediment CO_2 efflux

161   measurements, were collected using two small sediment cores (2 cm deep, 2 cm in diameter).

162   The sediment samples were kept frozen and stored in the dark prior to being analysed.

163   *Sediment carbon and nitrogen concentration:* Samples were dried (60°C for 48 hours) and

164   then pulverised using mortar and pestle. Total carbon (C) and nitrogen (N) concentration was

165   determined using an elemental analyser (TruSpec LECO CNS, Leco Corporation, St. Joseph,

166   MI). A subset of samples (n = 40, ranging from 0.17 to 12.63% total C) were acidified to

167   remove the inorganic C (Brodie et al., 2011). Briefly, 300 mg sediment was mixed with 0.5

168   ml dionized water and 1.5 ml of 20% HCl and then dried on a hot plate. Organic carbon

169   concentration was then determined using the elemental analyser.

170   *Grain size*: One sediment sample per site was analysed for grain size. The samples were

171   homogenised and a subsample of approximately 5 g of sediment was taken and digested in ~

172   9% hydrogen peroxide until bubbling ceased (Day, 1965). The sediment sample was then

173   wet sieved through 2000 µm and 63 µm mesh sieves. Pipette analysis was used to separate

174   the < 63 µm fraction into > 3.9 µm and ≤ 3.9 µm. All fractions were then dried at 60°C until a

175   constant weight was achieved (fractions were weighed at ~ 40 h and then again at 48 h).

176   Grain size fractions were calculated as percentage weight of gravel/shell hash (>2000 µm),

177   sand (63 – 2000 µm), silt (3.9 – 62.9 µm) and clay (≤ 3.9 µm).

178   *Chlorophyll α*: One sediment sample per site was analysed for chlorophyll α. Within one

179   month of sampling, the sample was freeze dried, weighed, then homogenised and a

180   subsample (~5 g) taken for analysis. Chlorophyll α was extracted by boiling the sediment in

181   90% ethanol, and the extract processed using a spectrophotometer (Spectrophotometer UV-

182   1800, Shimadzu, Kyoto, Japan) measuring absorption at wavelengths 665 and 750 nm. An

183   acidification step was used to separate degradation products from chlorophyll α (Hansson,

184   1988;Moed and Hallegraeff, 1978). Chlorophyll α concentration was calculated based on the

185   following equation:

186 Chlorophyll α (µg g^{-1} sediment) = $\left((750a - 665a) - (750 - 665)\right) \times Abs \times \dfrac{Ethanol\ in\ extraction\ (l)}{Sediment\ analysed\ (ug)}$

187 (2)

188 Where 750 and 665 is the absorption at wavelengths 750 and 665 nm, 750a and 665a is the

189 absorption at wavelengths 750 and 665 nm after acidification with 0.05 mL 1 mol HCl and

190 Abs is the absorbance correction for chlorophyll in ethanol (28.66)

191 *2.5 Tree and root biomass*

192 Within intact mangrove forests the tree height of the closest 5 mangrove trees to each

193 measurement/sampling point and the density (number of mangroves within a 2 m x 2 m area)

194 was recorded. Above ground biomass was estimated using the allometric equations developed

195 for *Avicennia marina* in New Zealand (Woodroffe, 1985):

196   Total above ground biomass$^{-1/3}$ (g dry weight) = -4.215 + 0.121 x Height (cm) (3)

197 At two sites, Mangere 1 (Auckland) and Hatea 1 (Northland) mangrove height exceeded the

198 range the allometric equation was designed for (determined from trees ranging in height from

199 40 to 248 cm) and measures of trunk diameter were instead used to estimate biomass (based

200 on the trunk diameter at 30 cm height of the closest 5 mangrove trees to each sampling

201 point):

202   Total above ground biomass $^{-1/3}$ (g dry weight) = 0.264 + 2.597 x Diameter (cm) (4)

203 At each clearance site a quadrat (0.5 m x 0.5 m) was sampled at three haphazardly placed

204 locations (within a 10 m radius). The following metrics were recorded within each quadrat:

205 the proportion of surface covered by mangrove leaf litter, proportion of surface covered by

206 macroalgae, number of mangrove seeds and seedlings, and number of pneumatophores.

207 Further, three randomly located root biomass cores (13 cm diameter, 15 cm depth) were

208 collected at each clearance site. After sorting, all vegetative material was air dried for one

209 week on aluminium trays, and then oven dried at 70 ℃ for approximately 4 days until dry

210 weight stabilised. No cores were collected from intact mangrove forest sites.

211 *2.6 Data analysis*

212 Replicates per site were averaged to provide mean site values. Mean site values were used in

213 subsequent data analysis. Coefficients of variation (CV) values were determined (standard

214 deviation/mean) to compare variation within and among sites.

215 Data were tested for normality using the Shapiro-Wilk test. As sediment CO_2 efflux rates in

216 the shading experiment were normally distributed, paired t-tests were used to determine

217   significant differences between shaded and control measurements. A Mann-Whitney Rank

218   Sum Test was used to determine significant differences in sediment CO_2 efflux, tree and

219   sediment characteristics, between intact and cleared mangrove sites, as data did not conform

220   to normality.

221   Backward multiple linear regression analysis was used to identify the sediment and

222   ecosystem characteristics that predicted CO_2 efflux. Levene's test was used to verify the

223   homogeneity of variance. Sediment CO_2 efflux values from intact mangrove forest site Matua

224   and cleared mangrove forest site Waiuku 2 were considered outliers (mean values were > 3

225   fold the overall mean and > 2 fold the next highest value) and not included in the regression

226   analysis.

227   Significance levels of 0.05 and 0.01 were used. All statistical analyses were conducted using

228   SPSS statistics software version 17 (SPSS Inc. Chicago, IL, USA).

229

3. Results

Shading experiment

No significant difference ($p > 0.05$) was detected in mean CO_2 efflux between shaded and control treatments (Figure 2). Removing the surface biofilm resulted in significantly higher CO_2 efflux ($p < 0.01$) for both shaded and control treatments (Figure 2).

Sediment CO_2 efflux and sediment characteristics from intact and cleared mangrove forest sites

Sediment CO_2 efflux varied considerably within and among sites. However, the mean variability within sites ($CV = 0.55$ for intact mangrove forests and 1.1 for cleared mangrove forests) was lower than mean variability among sites ($CV = 0.99$ for intact mangrove forests and 1.34 for cleared mangrove forests.

No significant difference in sediment CO_2 efflux was found between intact and cleared mangrove sites ($p > 0.05$) (Figure 3). The mean sediment CO_2 efflux rates for intact and cleared mangrove forest sites was 1.55 ± 0.43 µmol m^{-2} s^{-1} (n = 13) and 1.95 ± 0.53 µmol m^{-2} s^{-1} (n = 23), respectively. Removing the surface biofilm resulted in a higher CO_2 efflux at intact (2.34 fold increase) and cleared (1.66 fold increase) mangrove forest sites ($p < 0.05$) (Figure 3).

Mangrove above ground biomass ranged from 0.52 to 13.54 kg dry weight m^{-2}. Sediment characteristics varied considerably among sites and no significant differences ($p > 0.05$) were detected in sediment characteristics between intact and cleared mangrove forest sites (Table 1).

Variation in sediment CO_2 efflux was high among sites. Visual analysis indicated two sediment CO_2 efflux clusters within intact mangrove forests: high (>1.95 µmol m^{-2} s^{-1}) and low (<1.95 µmol m^{-2} s^{-1}). Mean sediment CO_2 efflux of the 'high efflux group' (Matua, Tairua 2, Uretara 1, Waikareao, and Welcome Bay 1) was 3.60 ± 0.94 µmol m^{-2} s^{-1} compared to 0.93 ± 0.27 µmol m^{-2} s^{-1} measured in the 'low efflux group'. Chlorophyll α concentration was significantly higher in the 'high efflux group' (53.31 ± 6.97 µg^{-1} g^{-1} sediment) than in the 'low efflux group' (26.63 ± 7.03 µg^{-1} g^{-1} sediment) ($p < 0.05$). In addition, sediment temperature (°C) was significantly higher in the 'high efflux group' (21.32 ± 0.99) than in the 'low efflux group' (17.87 ± 0.81) ($p < 0.05$) (supplementary table 2).

260   Similarly, cleared mangrove forest sites were grouped into two clusters: high (>1.55 µmol m^{-2}

261   s^{-1}) and low (<1.55 µmol m^{-2} s^{-1}). Mean sediment CO_2 efflux of the 'high efflux group'

262   (Mangere 1, Pahurehure 4, Waiuku 1, 2 and 3, Welcome Bay 1, Whangamata E) was $3.91 \pm$

263   0.82 µmol m^{-2} s^{-1} compared to to 0.52 ± 0.21 µmol m^{-2} s^{-1} measured in the 'low efflux

264   group'. Sediment organic carbon concentration ($4.22 \pm 0.84\%$ vs. $2.10 \pm 0.35\%$), nitrogen

265   concentration ($0.45 \pm 0.05\%$ vs. $0.26 \pm 0.04\%$), sediment sand content ($15.46 \pm 9.87\%$ vs.

266    $42.99 \pm 7.99\%$), and sediment clay content ($28.19 \pm 4.30\%$ vs. $15.09 \pm 2.64\%$) were

267   significantly higher in the 'high efflux group' than in the 'low efflux group' for cleared

268   mangrove forest sites ($p < 0.05$) (supplementary table 3).

269   *Regression analysis*

270   Backward multiple linear regression analysis revealed that mangrove biomass was the only

271   significant predictor of CO_2 efflux within intact mangrove forest sites ($r^2 = 0.49$, F = 9.43, p =

272   0.01) (Figure 4.A). Within the cleared sites, backward multiple linear regression analysis

273   revealed that sediment organic carbon concentration was the only significant predictor of CO_2

274   efflux ($r^2 = 0.32$, F = 9.23, $p < 0.01$) (Figure 4.B). No other significant relationships were

275   observed ($p > 0.05$ for individual coefficients).

276

4. Discussion

4.1 Sediment CO$_2$ efflux and sediment characteristics from intact temperate mangrove forest

Dark sediment CO$_2$ efflux in intact *Avicennia marina* forests across its distribution range in New Zealand (1.95 ± 0.53 µmol m^{-2} s^{-1} which equals 168.4 ± 45.8 mmol CO$_2$ m^{-2} d^{-1}) is similar to values reported for intact *Avicennia marina* forests in New Zealand (Lovelock, 2008; Lovelock et al., 2014), Australia (Livesley and Andrusiak, 2012) and New Caledonia (Leopold et al., 2013; Leopold et al., 2015) (Table 2). In contrast, our values are higher than the global estimates of sediment CO$_2$ efflux from intact mangrove forests including a number of other tropical mangrove species (0.71 ± 0.65 µmol m^{-2} s^{-1} (Bouillon et al., 2008); 0.80 ± 0.09 µmol m^{-2} s^{-1} (Alongi, 2014)) (Table 2). Higher sediment CO$_2$ efflux observed within our study may partly be explained by the inclusion of crab burrows and pneumatophores within flux measurements. The omission of crab burrows and pneumatophores has previously been proposed as a potential explanation of why global estimates may be underestimated (Bouillon et al., 2008). Crab burrows have been shown to increase CO$_2$ efflux by increasing the surface area for sediment-air exchange of CO$_2$ (Kristensen et al., 2008) and enhancing carbon decomposition processes (Pülmanns et al., 2014). Pneumatophores have been associated with increased CO$_2$ emissions by efficient translocation of CO$_2$ exchange from deeper sediments (Bouillon et al., 2008; Kristensen et al., 2008).

We found a negative relationship between mangrove above ground biomass and sediment CO$_2$ efflux across the 13 intact mangrove forests. The above ground biomass across the investigated *Avicennia marina* forests (5.2 to 135 t dry weight ha^{-1}) is considerably lower than the above ground biomass in many tropical mangrove forests (35 to over 400 t dry weight ha^{-1}) (Komiyama et al., 2008). Lower tree biomass associated with low forest cover may lead to increased light availability and sediment temperature, which in turn may result in a higher abundance and activity of microbial communities. Respiration from microbial communities growing on the sediment surface contribute a considerable proportion to total CO$_2$ efflux from mangrove sediments, as shown in a New Caledonian *Avicennia marina* forest (Leopold et al., 2013). High sediment chlorophyll α concentrations and the presence of algal mats characterising the 'high efflux sites" also suggest that respiration by photosynthetic communities can be a significant contributor to CO$_2$ efflux by remineralization of organic material (Decho, 2000). Further, higher sediment temperature in

309 the 'high efflux sites' is in line with findings from other mangrove forests (e.g. Leopold et al.,

310 2015) and many terrestrial ecosystems (e.g. Davidson and Janssens, 2006) as temperature

311 influences both the autotrophic and heterotrophic activity (Raich and Schlesinger, 1992).

312 We note that all sediment CO_2 efflux measurements in this study were made at low to mid-

313 tide. The efflux of CO_2 from mangrove sediment during low tide can be up to 40% greater

314 than during tidal immersion as molecular diffusion of CO_2 is faster when sediments are

315 aerated and the surface area for aerobic respiration and chemical oxidation increases (Alongi,

316 2009). However, benthic light availability is also reduced during tidal immersion, which may

317 result in increased respiration by the microphytobenthos (Billerbeck et al., 2007).

318 *4.2 Sediment CO_2 efflux and sediment characteristics of cleared mangrove forest*

319 Dark sediment CO_2 efflux in cleared *Avicennia marina* forests in New Zealand (1.55 ± 0.43

320 µmol m^{-2} s^{-1} which equals 133.9 ± 37.2 mmol CO_2 m^{-2} d^{-1}) is similar to sediment CO_2 efflux

321 following the clearance of tropical mangrove (Lovelock et al., 2011;Sidik and Lovelock,

322 2013;Lang'at et al., 2014). Higher sediment CO_2 efflux rates (2.1 to 7.6 µmol m^{-2} s^{-1}

323 depending on the time since clearing) were measured in cleared peat mangrove stands in

324 Belize (Lovelock et al., 2011).

325 We did not find a significant difference in sediment CO_2 efflux between intact and cleared

326 mangrove forest sites. Further, we did not find a relationship between time since clearing and

327 sediment CO_2 efflux. In contrast, sediment CO_2 efflux from cleared peat mangrove forests in

328 Belize declined logarithmically over a 20 year period (Lovelock et al., 2011). Two months

329 after the clearing of mangroves in Kenya, sediment CO_2 efflux increased approximately two

330 fold before returning to comparable levels to adjacent intact mangrove forests approximately

331 five months after clearance (Lang'at et al., 2014). A number of factors such as differences in

332 site sediment characteristics, size, exposure, and method of clearance may confound the

333 effect of time since clearing on sediment CO_2 efflux in our study.

334 Sediment CO_2 efflux in cleared sites was positively related to sediment organic carbon

335 concentration. This is in line with the findings reported for the clearing of peat mangroves

336 where the rate of CO_2 efflux was related to the microbial degradation of organic matter in the

337 sediments (Lovelock et al., 2011). Sediment organic carbon concentrations in the cleared

338 sites (2.74 ± 0.40%) are comparable to the sediment organic carbon concentration measured

339 in a mangrove forest in Auckland, New Zealand (Yang et al., 2013) and *Avicennia marina*

340 forests south of Melbourne, Australia (Livesley and Andrusiak, 2012). The mean sediment

carbon concentration in mangrove sediments collected across the globe is 2.2% (Kristensen et al., 2008). The highest sediment CO_2 efflux rates were measured at sites where large areas were cleared (>1 ha) using mechanical diggers and where the mulch was left in place. Increased sediment organic carbon and nitrogen concentrations resulting from the mulch input explain higher sediment CO_2 efflux at these locations. High clay content found at these sites may have also contributed to the accumulation of sediment carbon, which has been shown to be associated with higher CO_2 efflux in tropical mangrove forests (Leopold et al., 2013; Chen et al., 2010; Chen et al., 2012; Chen et al., 2014). Nitrogen enrichment has also been found to result in increased sediment CO_2 efflux, in particular dwarf/stunted mangrove forests (Lovelock et al., 2014). While no significant correlation was observed between CO_2 efflux and mangrove root biomass in our study, increased CO_2 efflux following mangrove clearance has previously been attributed to the rapid decomposition of fine root material related to increased sediment temperatures following the loss of canopy cover (Lang'at et al., 2014).

The clearance process typically includes considerable sediment disturbance, particularly when mechanical diggers are used (Lundquist et al., 2014a). The tracking and raking of the sediment creates compacted and mixed areas where deeper anoxic sediment is brought to the surface (*pers. obs*). Increased sediment CO_2 efflux has been observed within intact mangrove forest following disturbance of the top 30 cm of the sediment, however the effect was transitory, returning to pre disturbed levels within two days (Lovelock et al., 2011).

The area of clearing, shape and exposure may also influence CO_2 efflux as these factors influence site recovery. For example, smaller more exposed clearance sites at the edge of mangrove forests may be more likely to transition towards tidal flat characteristics (i.e. coarser sediment grain size, lower organic carbon and chlorophyll α concentration) than larger, less exposed sites where limited sediment mobilisation occurs (Lundquist et al., 2014b). Higher sediment carbon concentrations have been measured in older mangrove forests, growing further inland compared to younger mangrove forests, growing at the expanding seaward edge (Lovelock et al., 2010). This may also be related to the protection offered by seaward mangroves, enabling greater accumulation of carbon enriched mangrove detritus within the centre of the stand (Yang et al., 2013).

4.3 Sediment CO₂ uptake

Sediment CO_2 uptake (negative flux) was observed at one intact (Hatea 1) and three cleared (Tairua 3, Whangamata 1, Hatea 1) mangrove forest sites. CO_2 uptake has also been reported in other mangrove efflux studies (Lovelock, 2008; Lovelock et al., 2014; Leopold et al., 2015). CO_2 uptake has been explained by the presence of biofilm microbial communities, as CO_2 uptake changed to efflux following biofilm removal (Leopold et al. (2015). In other habitats, CO_2 uptake from terrestrial shrub sediment has been attributed to sediment effusion-dissolution processes driven by sediment pH and moisture (Ma et al., 2013). CO_2 uptake from wetland sediment has been attributed to the drawdown of CO_2 into the sediment during large ebbing or very low tides (Krauss and Whitbeck, 2012).

Microphytobenthos have been shown to be significant contributors to benthic primary productivity (Kristensen and Alongi, 2006; Bouillon et al., 2008; Oakes and Eyre, 2014). Due to the short duration of our measurements (90 seconds), CO_2 uptake might be explained by the continuation of photosynthetic activity by surface biofilm communities at the onset of dark measurements until coenzymes are depleted (NADPH, ATP) (Leopold et al. (2015). However, the results from our shading results suggest that this was not the case, as we did not see significantly higher CO_2 efflux from sediment that was pre-shaded compared to sediment which had not been pre shaded.

Another possibility is that the decrease in CO_2 concentration within the chamber observed at these sites is driven by the leakage of CO_2 from dark chamber measurements, via cracks, fissures or burrows in the surface sediment. The removal of the surface biofilm resulted in CO_2 emission even at the sites where CO_2 uptake was previously observed. This is possibly related to homogenising the sediment surface following biofilm removal, with cracks or burrows covered by scraped sediment, minimising CO_2 leakage to adjacent non-shaded microphytobenthos. Other studies have suggested that the biofilm may also act as a barrier to the flow of CO_2 from deeper sediment, which when removed results in a rapid increase in CO_2 efflux (Leopold et al., 2013; Leopold et al., 2015).

Chemoautotrophs have also been shown to fix carbon in intertidal sediment under dark conditions (Lenk et al., 2011; Boschker et al., 2014). In particular, at the interface of aerobic and anaerobic zones where large amounts of reduced compounds, such as sulphur, accumulate (Thomsen and Kristensin, 1997; Lenk et al., 2011; Santoro et al., 2013; Boschker et al., 2014). This is consistent with what is observed in mangrove sediment, where aerobic

403 to anaerobic transitions typically occur close to the sediment surface, with sulphur driven
404 processes likely to dominate in anaerobic conditions (Kristensen et al., 2008).

405 **4.4 Conclusions**

406 Mangrove deforestation is occurring at a rapid rate and the impacts of clearance are of
407 immediate environmental concern. This is the first study to investigate the effect of clearing
408 on sediment CO_2 efflux in temperate *Avicennia marina* forests. We found that rates of
409 sediment CO_2 efflux from cleared and intact temperate *Avicennia marina* forests are
410 comparable to rates observed in the tropics. High variability between sites due to age, size
411 and methodology of clearings, and underlying (and resulting) environmental characteristics
412 (e.g., sediment grain size, organic content) resulted in no significant differences between
413 intact and cleared sites. Regardless, our results suggest that greater consideration should be
414 made regarding the rate of carbon released from mangrove forest following clearance and the
415 relative contribution to the atmosphere.

Acknowledgements

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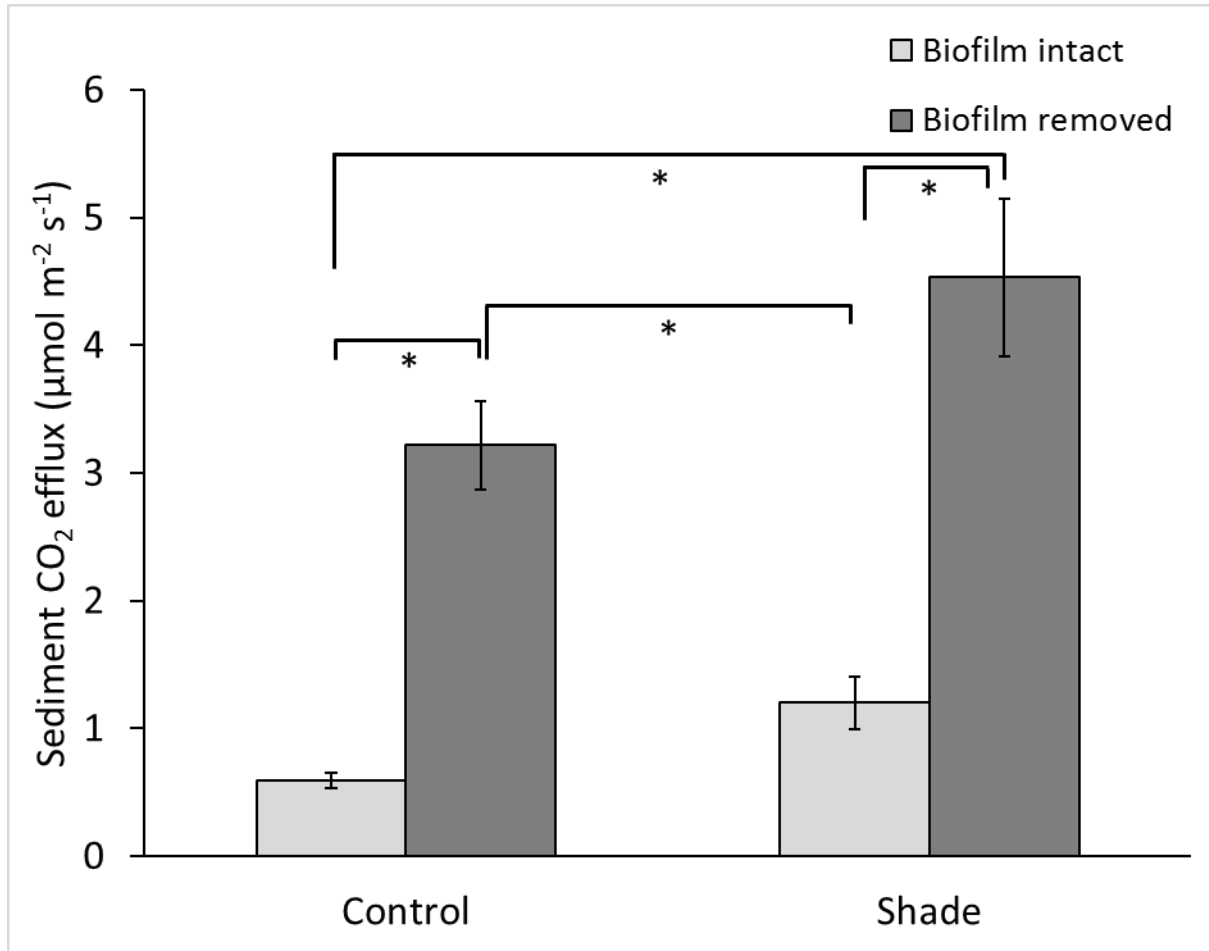
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Tables and figures
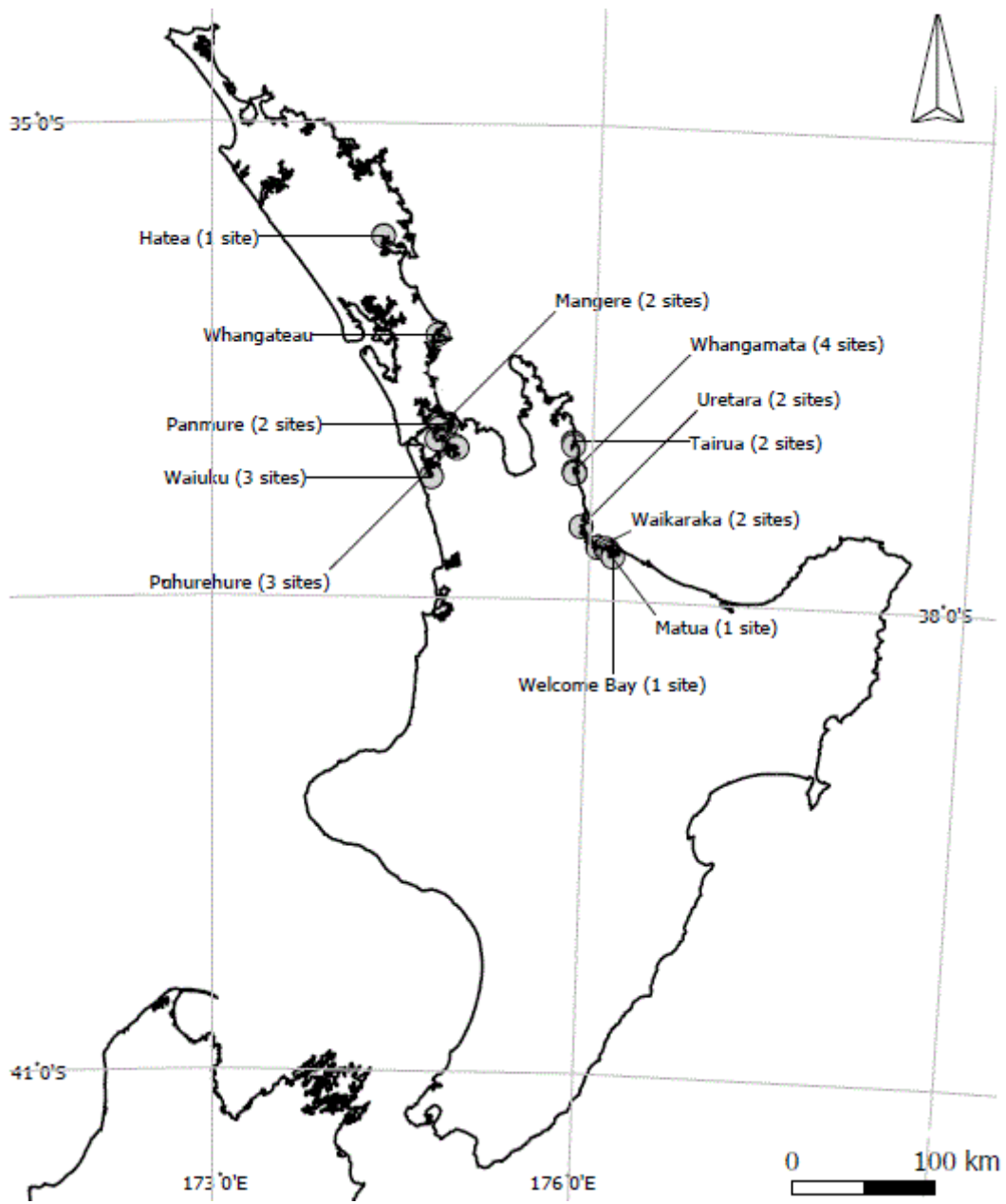
569 Figure 1: Location of the cleared mangrove sites (•) and estuary locations, throughout North
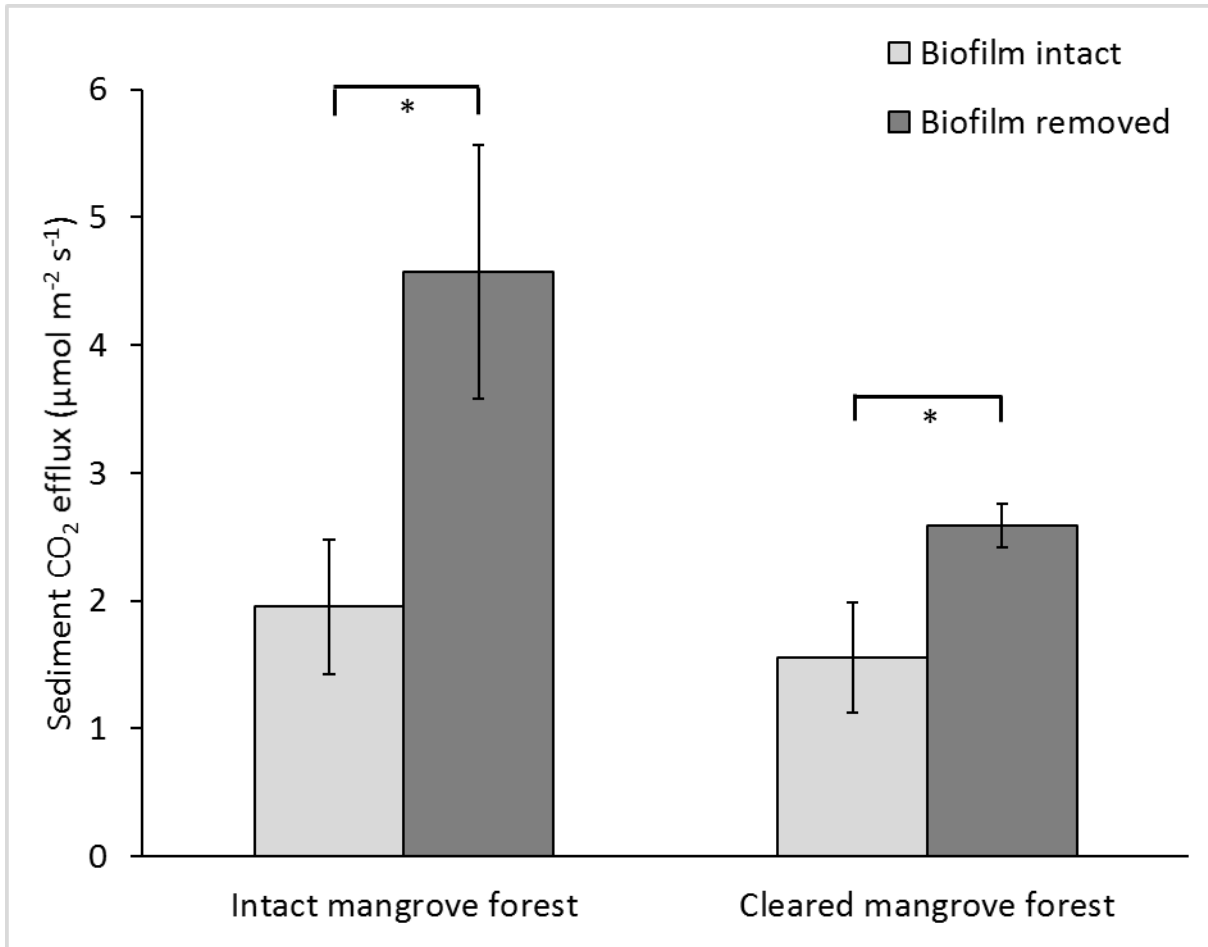570 Island, New Zealand.

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572

Figure 2: Mean sediment ($\pm$ SE) CO_2 efflux (μmol m^{-2} s^{-1}) before and after surface biofilm was
removed, from control (n = 6), and pre-shaded sediment (n = 6) at intact mangrove site Hatea 1.
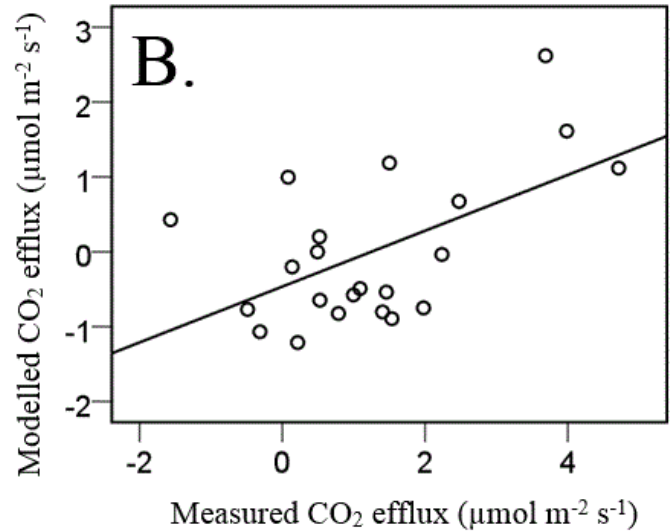*significant difference (p < 0.05)

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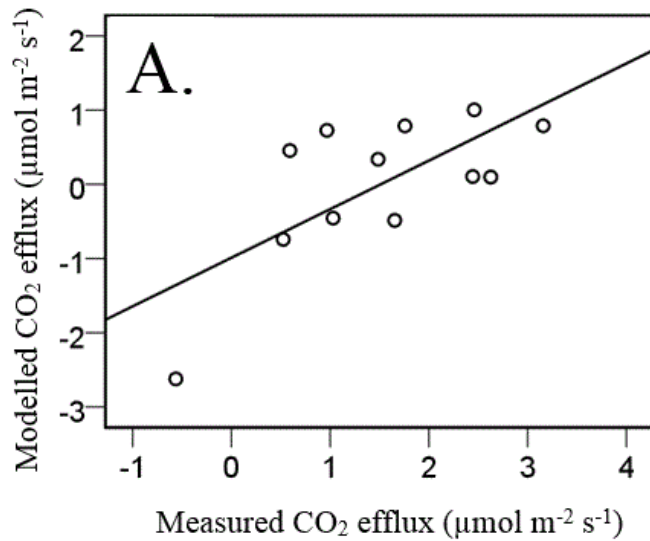

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578 Figure 3: Mean sediment ($\pm$ SE) CO_2 efflux (μmol m^{-2} s^{-1}) before and after surface biofilm was
579 removed, from intact mangrove forest (13 sites), and cleared mangrove forest (23 sites). *significant
580 difference ($p < 0.05$).

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Figure 4: Model A. Modelled values of mangrove forest CO_2 efflux compared to measured CO_2 efflux
($y = -0.73 + 0.59$ x mangrove biomass, $r^2 = 0.49$, $p < 0.01$). Model B. Modelled values of cleared
mangrove forest CO_2 efflux compared to measured CO_2 efflux ($y = -0.47 + 0.37$ x sediment organic
carbon concentration, $r^2 = 0.32$, $p < 0.01$).

587

588   Table 1: Mean site characteristics from intact and cleared mangrove sites, ± SE.

	Mangrove (n = 13)	Clearance (n = 23)
Mangrove biomass (kg dry weight m^{-2})	4.35 ± 0.93	0
Mangrove root mass (kg dry weight m$^{-3,}$ 15 cm depth)	*no data*	9.45 ± 1.00
Mangrove pneumatophore abundance (n m^{-2})	*no data*	257.32 ± 86.72
Time since clearance (yr^{-1})	-	2.89 ± 0.44
Sediment characteristics		
Organic carbon (%)	3.60 ± 0.73	2.74 ± 0.40
Nitrogen (%)	0.47 ± 0.10	0.32 ± 0.04
Gravel (%)	3.71 ± 2.25	1.54 ± 0.89
Sand (%)	29.44 ± 10.56	34.61 ± 6.76
Silt (%)	47.46 ± 7.07	44.78 ± 5.24
Clay (%)	16.61 ± 2.66	19.08 ± 2.55
Chlorophyll α (µg^{-1} g^{-1} sediment)	36.89 ± 6.16	26.82 ± 4.35
Sediment temperature (°C)	19.20 ± 0.17	20.20 ± 0.45

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Table 2: Comparison of mean estimates of sediment CO_2 efflux from a range of intact and cleared

mangrove forests, ± SE. * indicates no overall mean values provided

Intact Mangrove Forests

Species	Location, number of sites	Overall mean CO_2 efflux ± SE (mmol CO_2 m^{-2} d^{-1})	Overall mean CO_2 efflux ± SE (μmol CO_2 m^{-2} s^{-1})	Reference
Avicennia marina	New Zealand , 13	168.4 ± 45.8	1.95 ± 0.53	This study
Avicennia marina	New Zealand , 4	114.0 ± 19.9	1.32 ± 0.23	Lovelock et al, (2014)
Avicennia marina	South and North Australia , 4	107.1 ± 45.8	1.24 ± 0.53	Lovelock et al, (2014)
Avicennia marina	New Caledonia, 1	88.2 ± 23.7	1.02 ± 0.27	Leopold et al., (2013)
Avicennia marina	South Australia, 3	*Ranging from 73.73 to 117.89 throughout the year	*Ranging from 0.85 to 1.36 throughout the year	Livesley and Andrusiak (2012)
Global estimate, 82		61 ± 56	0.71 ± 0.65	Bouillon et al., (20080
Global estimate, 140		69 ± 8	0.80 ± 0.09	Alongi, (2014)

Cleared Mangrove Forests

Species	Location, number of sites	Overall mean CO_2 efflux ± SE (mmol CO_2 m^{-2} d^{-1})	Overall mean CO_2 efflux ± SE (μmol CO_2 m^{-2} s^{-1})	Source
Avicennia marina	New Zealand , 23	133.9 ± 37.2 (0 - 8 years since clearing)	1.55 ± 0.43 (0 - 8 years since clearing)	This study
Rhizophora mangle – peat soils	Twin Cays, Belize, 5	*Declining from 658.3 to 181.4 over 20 years	*Declining from 2.10 to 7.72 over 20 years	Lovelock et al., (2011)
Tropical mangrove	Bali, Indonesia, 1	*Shrimp pond floors: 99.4; Shrimp pond walls: 272.2	*Shrimp pond floors: 1.15; Shrimp pond walls: 3.15	Sidik and Lovelock, (2013)
Tropical mangrove	Gazi Bay, Mombasa, Kenya	88.62 (343 days since clearing)	1.03 (343 days since clearing)	Lang'at et al., (2014)

593