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1 **Organic carbon inventories in natural and restored Ecuadorian mangrove forests**

2

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18

19 **Abstract**

20 Because mangroves can capture and store organic carbon, their protection and restoration
21 is an obvious component of climate change mitigation. However, there are few empirical
22 measurements of long-term carbon storage in mangroves or of how storage varies across
23 environmental gradients. The context dependency of this process combined with geographically
24 limited field sampling has made it difficult to generalize regional and global rates of mangrove
25 carbon sequestration. This has in turn hampered the inclusion of sequestration by mangroves in
26 carbon cycle models and in carbon offset markets. The purpose of this study was to estimate the
27 relative carbon capture and storage potential in natural and restored mangrove forests. We
28 measured depth profiles of soil organic carbon content in 72 cores collected from six sites (three
29 natural, two restored, and one afforested) surrounding Muisne, Ecuador. Samples up to 1 m deep
30 were analyzed for organic matter content using loss-on-ignition and values were converted to
31 organic carbon content using an accepted ratio of 1.72 (g/g). Results suggest that average soil
32 carbon storage is $0.055 \pm 0.002 \text{ g}\cdot\text{cm}^{-3}$ ($11.3 \pm 0.8\%$ carbon content by dry mass, mean \pm 1 SE)
33 up to 1 m deep in natural sites, and $0.058 \pm 0.002 \text{ g}\cdot\text{cm}^{-3}$ ($8.0 \pm 0.3\%$) in restored sites. These
34 estimates are concordant with published global averages. Evidence of equivalent carbon stocks
35 in restored and afforested mangrove patches emphasizes the carbon sink potential for
36 reestablished mangrove systems. We found no relationship between sediment carbon storage
37 and aboveground biomass, forest structure, or within-patch location. Our results demonstrate the
38 long-term carbon storage potential of natural mangroves, high effectiveness of mangrove
39 restoration and afforestation, a lack of predictability in carbon storage strictly based on
40 aboveground parameters, and the need to establish standardized protocol for quantifying
41 mangrove sediment carbon stocks.

42 Introduction

43 The concentration of atmospheric CO₂ has increased by forty-percent since the beginning
44 of the industrial revolution and continues to increase concentrations by 2 ppm annually (Dedysch
45 et al. 2001, Le Quéré et al. 2012). As a result, we face a warming planet, rising seas, changing
46 precipitation patterns, and decreasing biodiversity (2012). Identifying effective, efficient, and
47 politically acceptable approaches to reduce the atmospheric concentration of CO₂ is thus one of
48 society's most pressing goals. Reducing atmospheric CO₂ via carbon sequestration – transferring
49 carbon to a safe biological or geological reservoir – is one such solution.

50 Terrestrial vegetation plays a key role in the global carbon cycle as both a sink and a
51 source of anthropogenic CO₂: total forest carbon uptake is $2.3 \pm 0.4 \text{ Pg C yr}^{-1}$ (Pan et al. 2011),
52 whereas the loss of vegetation via land use change adds $1.1 \pm 0.7 \text{ Pg C yr}^{-1}$. While terrestrial
53 forests as a whole are a net sink, tropical land use change emits $1.3 \pm 0.7 \text{ Pg C yr}^{-1}$ (Pan et al.
54 2011). Conservation of existing vegetation is therefore critical for preventing further carbon
55 emissions as well as for preserving carbon sequestration potential.

56 Despite the greater area of terrestrial carbon sinks (Schlesinger 1997), coastal carbon
57 sinks have comparable global carbon sequestration values: total global carbon uptake in
58 mangroves, salt marshes, and seagrass beds is estimated at 84-233 Tg C yr⁻¹ and uptake in
59 terrestrial systems is estimated at 180.8 Tg C yr⁻¹ (Kauffman et al. , Donato et al. 2011, McLeod
60 et al. 2011). In coastal ecosystems, high rates of uptake reflect high sediment accumulation rates
61 ranging from 18 to 1713 g C m⁻² yr⁻¹ (McLeod et al. 2011); organic carbon burial occurs as
62 sediment is accreted vertically during periods such as the present, when sea level is rising
63 (Ellison 2008).

64 On an aerial basis, mangroves display some of the highest rates of carbon burial and storage
65 among vegetated habitats, sequestering $2.26 \pm 0.39 \text{ Mg C ha}^{-1} \text{ yr}^{-1}$ and storing an estimated 1,023
66 Mg C ha^{-1} in aboveground and sediment stores combined (Kauffman et al. , Donato et al. 2011,
67 McLeod et al. 2011). Their elaborate root structures slow the rate of water movement and
68 thereby create an environment conducive for the settling of clay and silt particles (Wolanski
69 1995, Young and Harvey 1996). The carbon buried in these systems has been traced to not only
70 autochthonous sources such as litterfall, benthic macroalgae, and root decay, but also imported
71 sources such as seagrass and phytoplankton detritus, showing that mangrove forests provide
72 broad-scale sink benefits (Kristensen 2007, McLeod et al. 2011).

73 International carbon marketing systems such as REDD+ (Reduced Emissions from
74 Deforestation and Forest Degradation) place forest conservation projects in the context of the
75 global carbon offsets market. Such marketing requires accounting for the dynamic nature of
76 accumulation rates over temporal and geographic scales which are still not fully understood
77 (Alongi 2011). However, it is becoming increasingly clear that mangrove conservation (in a
78 carbon trading context) is more valuable for preventing carbon release from deforestation than
79 for continuously accounting for new sequestration (Kauffman et al. , Alongi 2011, Donato et al.
80 2012, Fourqurean et al. 2012).

81 Mangrove deforestation generates emissions of 0.02-0.12 Pg annually Cyr^{-1} , the equivalent of
82 2-10% of emissions from tropical deforestation despite the fact that global mangrove area is <
83 1% of that of tropical forest area (Kauffman et al. , van der Werf et al. 2009, Giri et al. 2011,
84 Donato et al. 2012, Le Quéré et al. 2012). Nearly half of the world's mangroves forests have
85 already been cleared, and the recent deforestation rate is roughly 1-3% annually (Alongi 2002,
86 Bouillon et al. 2008, Donato et al. 2011). Mangroves are usually cleared for development or

87 conversion to aquaculture (Alongi 2002). Upon clearing, both the aboveground biomass and
88 sediment carbon stores are disturbed and/or aerated, increasing microbial activity (Granek and
89 Ruttenberg 2008, Couwenberg et al. 2010, Lovelock et al. 2011, Pendleton et al. 2012).

90 Though conservation of these ecosystems could be incentivized by recognizing both their
91 continuing sink potential and the adverse effects of deforestation via carbon release, the
92 application of existing information to conservation initiatives is limited by a lack of empirical
93 data. Most carbon storage and sequestration studies are from Florida, China, the Indo-Pacific,
94 Australia, and the Brazilian coastline, despite global distribution of mangroves on coastlines
95 between 0 and 30 degrees latitude (Fujimoto et al. 1999, Cebrian 2002, Chmura et al. 2003).
96 Mangrove storage and sequestration estimates in South America, especially on its Pacific coast,
97 have been extremely rare thus far.

98 In addition, methodological discrepancies have led to significantly different results which are
99 difficult to interpret. Carbon storage and sequestration quantification is limited by a lack of
100 concurrent data on depth, bulk density, carbon concentration, and sediment accumulation rates
101 (Kauffman et al. , Alongi 2011, Donato et al. 2011). Finally, though the value of mangrove
102 conservation can be inferred from previous observations of their natural state, little work has
103 addressed the effectiveness of restoring these ecosystems in terms of carbon storage and
104 sequestration (Laffoley and Grimsditch 2009).

105 The purpose of the study was to understanding how mangrove carbon storage varies with
106 environmental context. Primarily, we asked how soil carbon standing stocks vary based on
107 forest structure, locations within mangrove patches (defined here as continuous stands of
108 mangroves), and patch land use history. Additionally, we examined how carbon concentration
109 varies with soil depth in a given location and how these concentrations may be most accurately

110 determined. We used these estimates to analyze the carbon storage efficiency of restoring
111 mangroves in sites previously cleared for shrimp farming, and introducing mangroves to replace
112 native vegetation.

113

114 **Methods**

115 Study Sites

116 We surveyed the forest and collected soil cores at six sites in coastal Ecuador. The sites
117 are located between 0°32'N and 0°38'N and surround the island of Muisne in the Esmeraldas
118 province of Ecuador. This area is unique for its community-driven focus on conservation and
119 successful restoration of mangrove forests. We selected three natural sites, two restored sites,
120 and one afforested site that have similar geography and comparable patch sizes. All sites are
121 mainly monocultures of red mangroves (*Rhizophora mangle*) with scattered white (*Laguncularia*
122 *racemosa*) and black mangroves (*Avicennia germinans*) at the fringes.

123 We determined site histories using a combination of unpublished maps and land use
124 documents from the Jatun Sacha Foundation (a local non-profit conservation organization),
125 interviews with local residents and property owners, and official maps from Ecuador's Instituto
126 Geografico Militar (Andres Leith, pers. comm). The natural sites (Nat A, Nat B, and Nat C) are
127 located in mangrove forest that has been undisturbed for at least three decades (and likely much
128 longer). The restored sites (Rest A and Rest B) were predominantly mangrove forest until the
129 1980's, at which point they were dredged, diked, and filled for use as shrimp farms until the time
130 of restoration in 2003 (Rest A) or 2000-2002 (Rest B). These sites, having been re-established
131 by planting of red mangrove propagules gathered from existing populations, are characterized by

132 smaller trees with more uniform ages. The afforested site (Aff) is an area that was converted
133 from halophytic ferns to mangrove in 1993.

134 At each of these sites, we established six plots using a random selection of coordinates.
135 For each plot, we took forestry surveys and outlined a 1x1 m quadrat that could be used to take
136 replicate soil core samples. We then mapped site coordinates and used Google Earth to measure
137 the shortest straight-line distance to the mangrove patch edge to determine a rough estimate of
138 distance to the estuarine shoreline. We estimate a measurement error of approximately 30 m on
139 coordinate and distance measurements due to; a) the difficulty of obtaining satellite signals from
140 within the dense mangrove canopy and b) inaccuracy in the simple straight line measurements
141 made using Google Earth.

142

143 Forestry Surveys

144

145 In order to test whether sediment carbon storage varied with forest composition and
146 density, we collected and analyzed forestry data using the protocol outlined in the GOF-C-GOLD
147 sourcebook published by REDD (Reduced Emissions from Deforestation and Forest
148 Degradation) (Pearson et al. 2005). At each plot, we first delineated a 2x2 m quadrat, in which
149 we used a diameter tape to measure the DBH, or ‘diameter at breast height’ (height 1.3 m) of
150 each tree. In cases where the prop roots typical of *R. mangle* extended above breast height, we
151 took the diameter at 30 cm above the uppermost root connection to the main trunks (Komiyama
152 et al. 2005). Multiple trunks were individually measured for use in allometric equations but
153 noted as the same tree in tree density calculations (Clough et al. 1997). As per calculations
154 recommended by the GOF-C-GOLD Sourcebook, we used a nested plot design to measure total

155 forest biomass. If any DBH exceeded 5 cm, the 2x2 m was then extended to a 7x7 m plot, in
156 which we followed the same process for all trees with at least one trunk >5 cm in DBH. Finally,
157 if any trees in this plot exceeded 25 cm in diameter, we extended the quadrat to 25x25 m and
158 measured all trees with diameters >25 cm.

159 We used DBH data to derive aboveground biomass estimates using the species-specific
160 allometric equations recommended by (Komiyama et al. 2008):

161

162 *Rhizophora mangle*

163 (1) $W_{\text{top}}=0.178(\text{DBH})^{2.47}$, $r^2=0.98$, $n=17$

164

165 *Avicennia germinans*

166 (2) $W_{\text{top}}=0.140(\text{DBH})^{2.54}$, $r^2=0.99$, $n=21$

167

168 *Laguncularia racemosa*

169 (3) $W_{\text{top}}=0.209(\text{DBH})^{2.24}$, $r^2=0.99$, $n=17$

170

171 These equations accounted for all aboveground biomass. Estimates of biomass density at
172 the hectare scale were calculated by scaling up the 2x2, 7x7, and 25x25 m quadrat biomass and
173 tree totals to hectare totals.

174

175 Soil Core Collection

176 We collected two soil cores from each of the 36 plots using a 6.69 cm inner-diameter x 1
177 m length stainless steel core tube with a sharpened edge. The tube was equipped with a rubber

178 piston held by rope at the top of the soil surface (or water surface if the soil was submerged) to
179 minimize compaction as the core tube was pushed down. The piston was maintained in place
180 relative to the tube as the core was retrieved from the soil, ensuring soil retention. When the tube
181 reached the soil surface, a rubber plug was inserted into the bottom of the tube.

182 The core was sectioned in the field by propping the tube on a wooden dowel, removing
183 the upper rubber piston, and pushing down on the core barrel to extrude the soil upward. We
184 sampled 1 cm sections at 6 cm resolution, discarding the uppermost 5 cm as litter fall. Samples
185 were removed using a stainless steel knife run along the top edge of the core tube. We discarded
186 a 5 mm rind from each section to remove soil that may have been mixed due to friction along the
187 wall of the core tube. Soil samples were double sealed in Whirl-paks® and frozen.

188

189 Soil Analyses

190 To obtain bulk soil density, we removed visible root material; decaying plant matter and
191 dead wood were left in the sample. Root removal is necessary to measure soil density, but
192 results in underestimating organic carbon inventories, as the woody root matter accounts for an
193 average of 8.1% of the sample volume in samples where roots was removed. After root removal,
194 we transferred soil samples to tared aluminum foil boats, dried them at 105°C for 12 hours, and
195 reweighed each sample. The drying time was validated by drying a subset of 67 samples for 12,
196 24, and 48 hours; relative differences in mass between 12 hours and each of the longer durations
197 were 0.2% and 0.3%, respectively, so 12 hours was chosen as an acceptable drying time. Bulk
198 soil density was calculated as the mass of dry soil per volume of bulk soil. Bulk soil volume was
199 calculated for each sample using a 5.59 cm diameter (after discarding rind) and measured core

200 segment height, with the volume of the removed root matter subtracted (root matter volume was
201 measured to a precision of 0.2 cm³ using water displacement).

202 One replicate core from each plot was processed exclusively for loss-on-ignition (LOI).
203 Dried samples were ground and homogenized using a mortar and pestle until the material could
204 pass through a 2 mm mesh. We transferred the entire dry sample to a tared crucible to burn at
205 500°C for 12 hours, as recommended by Wang et al. (2011) for non-marine sediments. The
206 reported precision of the LOI method depends on soil type, but is always < ±15% of the
207 measured value (Wang et al. 2011). We did not measure LOI reproducibility because the entire
208 sample was combusted.

209 We tested the traditionally assumption that in general, organic matter (represented by
210 LOI) is comprised of 58% organic carbon, yielding a 1.72 conversion factor (Allen 1974).
211 Despite the likelihood that these assumptions provide only approximations, the 1.72 conversion
212 factor has been used to derive global estimates of mangrove carbon storage and sequestration
213 (Chmura et al. 2003, Duarte et al. 2005, McLeod et al. 2011). We examined this assumption by
214 sub-setting samples carbon analysis.

215 The second replicate core from selected plots—two natural, two restored, and two
216 afforested cores were chosen arbitrarily—was used for total organic carbon (TOC) analysis using
217 a Carlo-Erba Elemental Analyzer. These samples were dried, ground, and homogenized
218 following the procedure described above for LOI. Triplicate 7-10 mg aliquots of each dried and
219 homogenized sample were weighed into tared tin boats and fumed with gaseous HCl to remove
220 inorganic carbon. We followed the method of Hedges and Stern (Hedges and Stern 1984) except
221 that we used tin rather than silver sample boats. Tin reacts with HCl vapor to form SnCl₂,
222 possibly affecting the tare and causing the boats to become brittle. The reported precision of the

223 TOC method is $\pm 1\%$ of the measured value (Hedges and Stern 1984); however, precision of our
224 TOC analyses averaged $\pm 18\%$ (range: 2-45%), probably related the use of tin boats. This has
225 limited impact on our organic carbon inventories, since they are ultimately related to LOI, which
226 has similar reproducibility. The remaining soil from the second replicate core was analyzed for
227 LOI to provide paired data for forming the TOC-LOI calibration equation.

228

229 Statistical Analyses

230

231 We averaged sample measurements hierarchically to analyze on the levels of plot, site,
232 and classification. Whenever possible, we averaged measurements by depth from both replicate
233 cores in each plot ($n = 36$), and otherwise used the measurements from a single core ($n = 8$). In
234 cases where we looked at site-specific and classification-specific differences, we first averaged
235 plot measurements to compute averages by depth and/or carbon standing stocks. We took
236 carbon concentration to be the product of individual sample bulk density and %TOC values.

237 We used the R platform for all statistical analyses. We used the caTools package to
238 compute integrated loess curves ($\text{span} = 0.5$) over the maximum depth interval per set of plot
239 averages to calculate total carbon standing stock per unit area per plot. All integrations began at
240 5 cm of depth rather than at surface level to avoid the uncertainty introduced by extrapolation, so
241 we may have underestimated the carbon standing stocks. We separately integrated all plots with
242 core measurements > 70 cm in depth from 5 to 70 cm to compare sites and classifications without
243 the confounding effect of varying core lengths; we term these integration results *corrected*
244 *carbon stocks*.

245 We used linear mixed effects models to assess the effects of site, land history
246 classification, total aboveground biomass, tree density, species composition (percent trees which
247 were red mangroves versus white or black) and distance to estuarine shoreline on the corrected
248 carbon stocks using the NLME package in R. The Akaike information criterion (AIC) was used
249 to determine the best models and parameters using random components for site and classification
250 values. Additionally, we used a Welch Two Sample t-Test to compare natural and restored site
251 standing stocks using the corrected measurements (up to 70 cm and no further).

252

253 **Results**

254

255 Aboveground Biomass (AGB) and Tree Density

256 Natural sites and the afforested site had significantly higher AGB and significantly lower
257 tree density than the restored sites (Fig. 2; Table 1). As a mangrove forest matures, the trunks get
258 larger and more dispersed, with larger root boles which overlap in the areas between trees.

259 Similar AGB and tree density in afforested and natural sites suggests that 20 years is sufficient
260 for a mangrove forest in this region to reach maturity; lower AGB and higher tree density at the
261 restored sites suggests that the mangrove forest is still maturing 10 years after restoration. AGB
262 for all sites at the low range of previous estimates across all latitudes (Alongi 2002).

263

264 LOI vs. TOC

265 LOI values must be converted to TOC to accurately quantify soil organic carbon
266 inventories. The mass lost through combustion includes the non-mineral component of organic
267 matter as well as lattice water in clays and other soil components that are volatile at high

268 temperature; oxygen may be incorporated if nonvolatile oxides form during combustion. LOI is
269 sometimes converted to TOC using the van Bemmelen factor (TOC/LOI = 58%), but numerous
270 studies have shown that the TOC/LOI ratio can range over a factor of two (Howard and Howard
271 1990) and depends on soil type.

272 Our results suggested a strong linear correlation between % lost-on-ignition and % total organic
273 carbon content found via carbon analysis (Fig. 2, $R^2=0.89$, $p<0.001$): $TOC (\%) = 0.87 LOI (\%)$
274 $- 5.8$. The TOC/LOI ratio (87%) and the y-intercept of LOI vs. TOC suggest that these soils
275 contain almost 7% structural water or minerals that are volatile at 550 C. Howard and Howard
276 (1990) found that the TOC vs. LOI linear regression yielded the highest y-intercept (5.64) for
277 gley sediments high in clay content (mean 21.9%). This equation had a linear coefficient of 1.52
278 and an R^2 of 52%.

279 The coefficient of variation for our TOC analysis averaged $\pm 18\%$ (range 4% to 45%).
280 The reproducibility is well below the analytical precision under optimal conditions ($\pm 2\%$) and
281 may reflect instrumental variability or heterogeneity in the sediment. We therefore present a
282 range of %TOC values calculated using both the van Bemmelen factor and our conversion
283 equation.

284

285 Carbon Concentrations

286 As found in previous studies (Kauffman et al. , Avnimelech et al. 2001, Donato et al.
287 2011), our results suggested an inverse relationship between %total organic carbon (%TOC,
288 mass sediment organic carbon per mass sediment) and bulk density ($g\ cm^{-3}$, mass dry sediment
289 per volume wet sediment):

290

291 (4) %TOC = 6.044(BD)^{-0.775} (Figure 4, n=442)

292

293 Overall across all natural and restored sites and depths, median TOC content was found
294 to be 7.38% and average carbon concentration were found to be 55.9 ± 1.4 mg OC cm⁻³. There
295 appears to be no consistent change in %TOC in either classification over the 1 m depth interval
296 (Figure 5). Though a slight decrease is noted in both site classifications from 80-100 cm depth,
297 deeper samples would be necessary to verify whether or not this is a continuous pattern. A
298 significant peak is uniquely present in the %TOC content of the restored sites at approximately
299 30-60 cm. The same peak holds when measurements are converted to carbon concentrations
300 (Figure 6). After measurements were converted to corrected carbon standing stocks, results
301 suggested that restored sites contained more sediment carbon (411.6 ± 27.9 Mg C ha⁻¹) than
302 natural sites (365.3 ± 23.8 Mg C ha⁻¹), these differences were not statistically significant (two-
303 tailed t-test 0.22).

304 Analysis of carbon standing stock using the linear mixed effects models suggested that,
305 as predicted, core length is highly significant ($p < 0.001$) as a predictor of the total carbon
306 standing stock. No other variable was found to significantly improve the model, e.g., we found
307 no clear evidence of a relationship between distance to estuarine edge, species composition, or
308 site classification and standing stock, even when coordinates were included. Aboveground
309 biomasses and belowground standing stocks by site are presented in Table 1. A Mantel test
310 indicated there was a significant effect of location (UTM coordinates) on total sediment carbon
311 standing stock ($p = 0.05$) but not on total aboveground biomass ($p = 0.89$) but the addition of
312 coordinates to the linear mixed effects models had no effect.

313

314 **Discussion**

315

316 Carbon Standing Stocks

317 Carbon concentration (gC cm^{-3}) did not vary significantly between natural or restored
318 mangroves, suggesting that carbon standing stock in ten year old restored mangroves with
319 significantly less aboveground growth is approximately equivalent to stock in natural mangroves
320 that are likely at least 40-50 years old (Alongi 2002). Additionally, carbon concentration did not
321 vary with depth between 5 cm and up to 1 m, suggesting that significant decomposition does not
322 occur from the time that the organic carbon is buried until at least the time that this depth
323 represents. This finding was concordant with that of Donato and colleagues (2011), who
324 concluded that changes in each of these parameters occur deeper than approximately 1 m in
325 depth. Based on published averages of mangrove sediment accretion rates (Alongi 2012,
326 Breithaupt et al. 2012) our measured top 90 cm of sediment likely represent 280 ± 80 years (95%
327 C.I.) of sediment / carbon accumulation.

328 We also found that carbon standing stock up to 1 m in depth is strongly correlated with
329 core length. Though this relationship would be expected under the simple assumption that more
330 sediment analyzed implies more carbon to be found, our identification of the relationship
331 emphasizes two points regarding future quantification of globally distributed mangrove stocks.
332 The first is that shallower cores may be useful in calculating carbon stocks up to 1 m in depth,
333 potentially validating extrapolation (to a limit) of studies such as those presented by Chmura et
334 al. (2003) which included measurements from up to 0.5 m depth. The second point is that
335 calculation of carbon stocks requires an understanding of soil depth as it varies in mangroves
336 globally, as slight changes in this depth measurement have strong implications for the calculation

337 of total sediment carbon stock. Studies which address overall sediment depth have to this point
338 been rare, as can be seen in several meta-analyses and recommendations for future research
339 (Kauffman et al. , Chmura et al. 2003, Laffoley and Grimsditch 2009, Donato et al. 2012).

340 Additionally, we found that neither forest structure and composition nor distance from
341 the seaward edge are significant predictors of carbon standing stock up to 70 cm in depth.
342 Though the clear differences in aboveground biomass with forest maturity likely influence
343 immediate accretion and litterfall rates, the dynamic nature of these forests (i.e. tendency for
344 scour and/or deposition during storm surges) would prevent us from detecting those effects in
345 measurements of carbon storage over long time periods without intensive sampling.

346 347 Natural versus Restored and Afforested Site Parameters

348 We found that natural, restored, and afforested mangrove sites are equally important in
349 terms of current carbon standing stock, emphasizing the value of preservation of relatively young
350 forests as well as old growth stands--disturbance of either classification would aerate similar
351 quantities of sediment organic carbon. We found a 12.6% higher mean value for restored sites
352 than natural sites (365 Mg C ha⁻¹), despite the clearly later successional stages of the natural
353 sites. This implied that mangrove restoration of shrimp farms is effective at restoring ecosystem
354 function, at least in terms of carbon sink potential seen in the decade post-restoration. This
355 finding contradicts that of Osland et al. (2012) (Osland et al. 2012), who found lower rates of
356 carbon storage in restored mangroves.

357 The higher mean carbon stock of restored sites appears to be due to a peak in
358 concentrations at approximately 30-60 cm deep. Because the same peak was not present in the
359 afforested site profile, it could represent a relic of the shrimp farm history of the restored sites.

360 Higher concentration values could result from shrimp carcasses, ‘fertilizer’, or feces that
361 accumulated during the farming period and were buried when the mangroves were replanted and
362 began to accrete sediment. Because the shrimp farms are excavated and form low spots in the
363 landscape, they are prime areas for sedimentation as currents flow in and pool, especially if
364 mangroves are present to encourage the trapping of sediment particles. If this rapid
365 sedimentation indeed occurred, the theoretical 3 cm yr⁻¹ of accretion that our results would
366 suggest would rapidly place the high quantities of organic matter in an anaerobic environment
367 and potentially reduce the rate of decomposition. If this is indeed the case, restoration of shrimp
368 farm plots to mangroves mitigates much of the change that original shrimp farm construction
369 might have caused.

370

371 Current Context and Future Concerns

372 Geographically, our study is unique in that it provides the first estimate of mangrove
373 carbon storage on the Pacific coast of South America. Putting this into a global context, our
374 results are concordant with those published in meta-analyses that synthesize studies mainly from
375 Southeast Asia and Florida (Table 2). Our measurements come from equatorial mangroves,
376 which are thought to be among the highest productivity globally (Alongi 2002). This potential
377 geographical variation should be considered in extrapolations to global mangrove carbon storage.

378 Mangrove restoration is becoming increasingly attractive as we search for ways to
379 mitigate climate change. Though preservation of existing carbon stocks is a clear way to prevent
380 additional
381 emissions from deforestation, restored shrimp farms display even higher carbon standing stocks
382 than mangroves, which are thought to have some of the highest rates globally. It is likely that

383 having mangroves present promotes burial – rather than disturbance and aeration – of the carbon
384 present. Because there are very few studies of mangrove restoration potential in terms of carbon
385 storage, a proper evaluation will require additional studies in other areas where restoration may
386 be a viable option, perhaps with a specific focus on those regions (unlike ours) where
387 monocultures do not occur naturally as well as in restored zones. Long-term monitoring will be
388 needed to verify the continued storage of the carbon peaks we observed. Our study demonstrates
389 the potential for mangrove restoration to effectively sequester carbon.

390

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507 Table 1. Summary statistics per site (means \pm standard errors) for a soil depth of 71 cm
 508 (corrected carbon stocks) using both the 1.72 conversion factor and our conversion equation (*).

Site	Aboveground Biomass (Mg·Ha⁻¹)	Sediment Carbon Storage ((Mg·Ha⁻¹) ¹)	Sediment Carbon Storage ((Mg·Ha⁻¹) ¹)*
Nat A	70 \pm 18	448 \pm 143	397 \pm 175
Nat B	193 \pm 57	387 \pm 45	356 \pm 63
Nat C	39 \pm 11	386 \pm 61	374 \pm 177
Rest A	24 \pm 5	427 \pm 54	365 \pm 97
Rest B	46 \pm 10	395 \pm 22	321 \pm 71
Aff	93.3 \pm 1	399 \pm 22	304 \pm 67

509

510 Table 2. Comparison of natural and restored site carbon storage estimates to previously
 511 published estimates.

Source	Region(s)	Mean Soil Carbon	
		Concentration (g C cm ⁻³)	Core Length
Chmura et al. (2003)	Global	0.055	0.5 m
Donato et al. (2011)	Indo-Pacific	0.038 (Estuarine) 0.061 (Oceanic)	Variable, up to 3 m
Sifleet et al. (2011)	Global	0.015-0.115	Variable
Natural, this study	Ecuador	0.055 ± 0.002	0.65–1 m
Restored, this study	Ecuador	0.058 ± 0.002	0.65–1 m
Afforested, this study	Ecuador	0.056 ± 0.002	0.65–1 m

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514 **Figure Legends**

515

516 Figure 1. (clockwise from top left) prop root structure on red mangroves at Site Nat 2; exposed
517 root structures at low tide show accumulation of sediment; field extrusion method: discard of 5
518 cm; core tube fully submerged in sediment with rubber piston held at the surface of the ground.

519

520 Figure 2. Comparison of methods used to derive %TOC values from %LOI measurements.
521 Studies using LOI as a proxy for TOC have traditionally used the 1.72 conversion factor (red);
522 our data suggest the use of a linear regression (black).

523 Figure 3. Restored sites tended to have higher total trees and lower total biomass estimates than
524 the natural sites. The afforested site overall had fewer trees than either other classification, but
525 more closely resembled the forest structure of the natural sites.

526

527 Figure 4. Inverse relationship between %TOC and bulk density (Eqn. 2)

528

529 Figure 5. %TOC profiles (means +/- standard error using 1.72 conversion factor) suggest
530 negligible differences between the two main site classifications, but a slight peak in the restored
531 site profile is noted between 40-60 cm of depth.

532

533 Figure 6. Carbon concentration profiles (means +/- standard error using 1.72 conversion factor)
534 suggest negligible differences between the two main site classifications, but again, a slight peak
535 in the restored site profile is noted between 20 and 60 cm of depth.

536

537 Figure 1.

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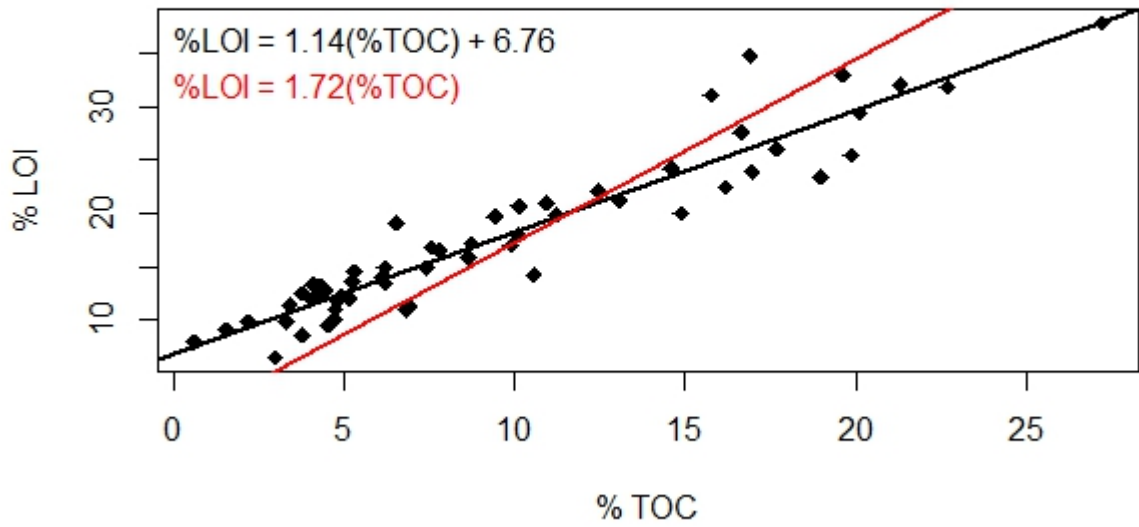


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543 Figure 2.

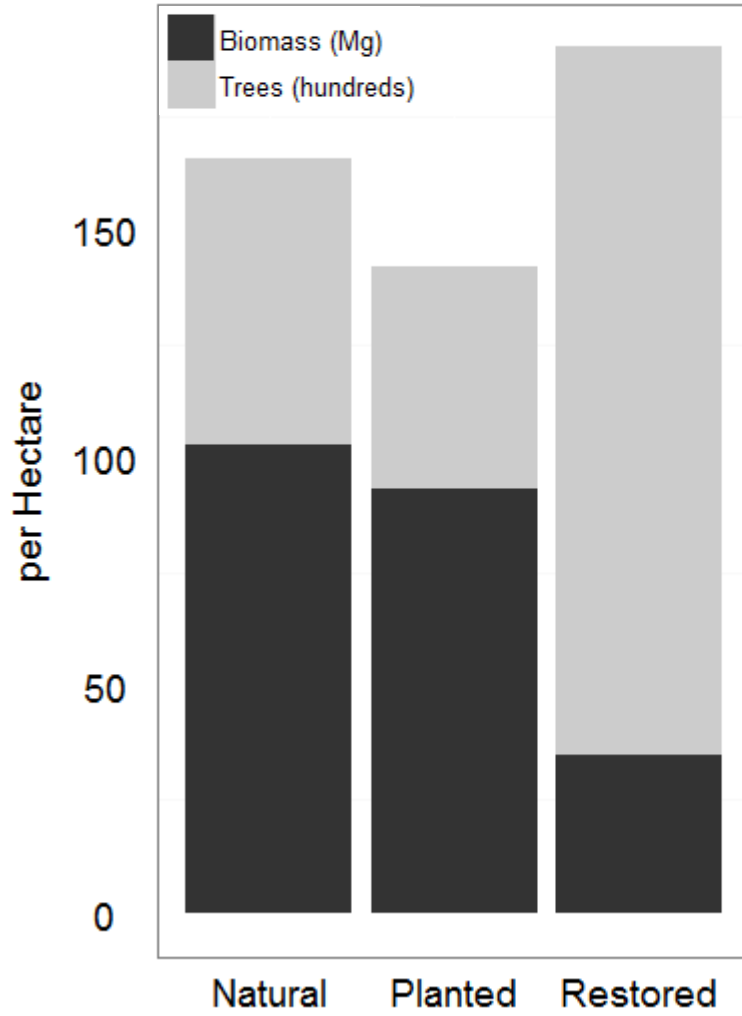


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546 Figure 3.

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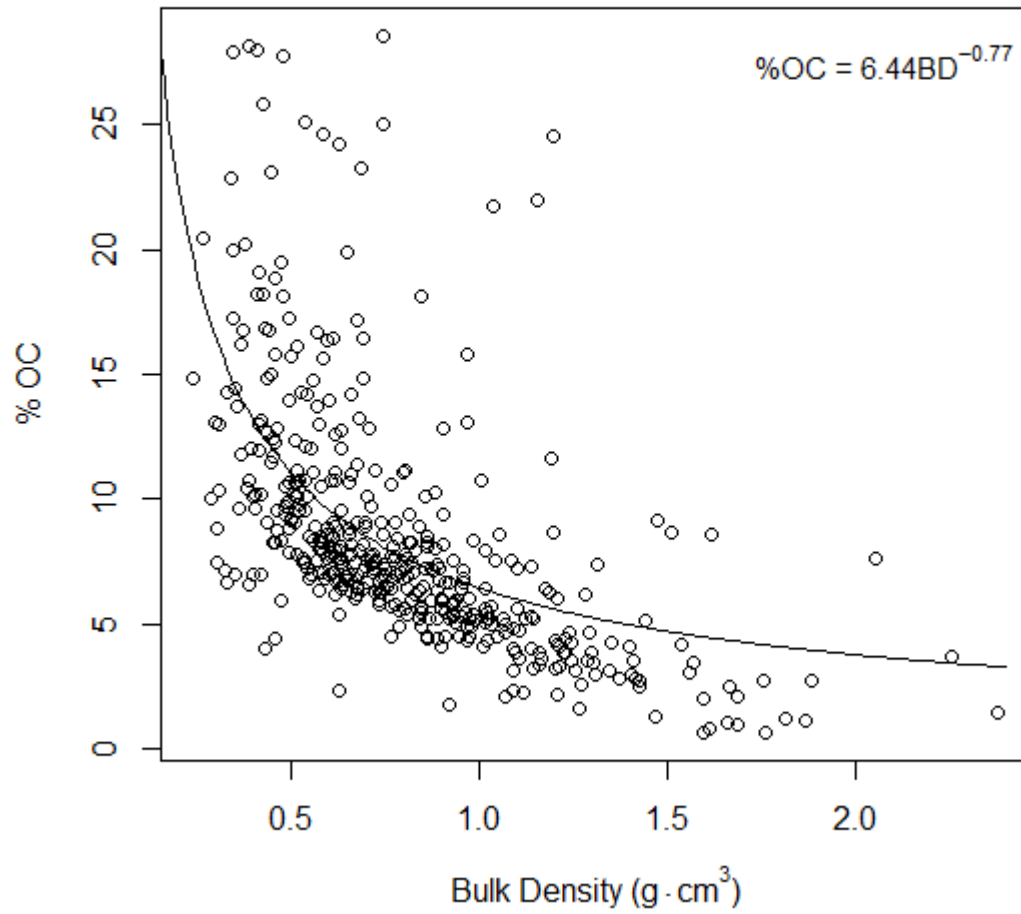
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Figure 4.

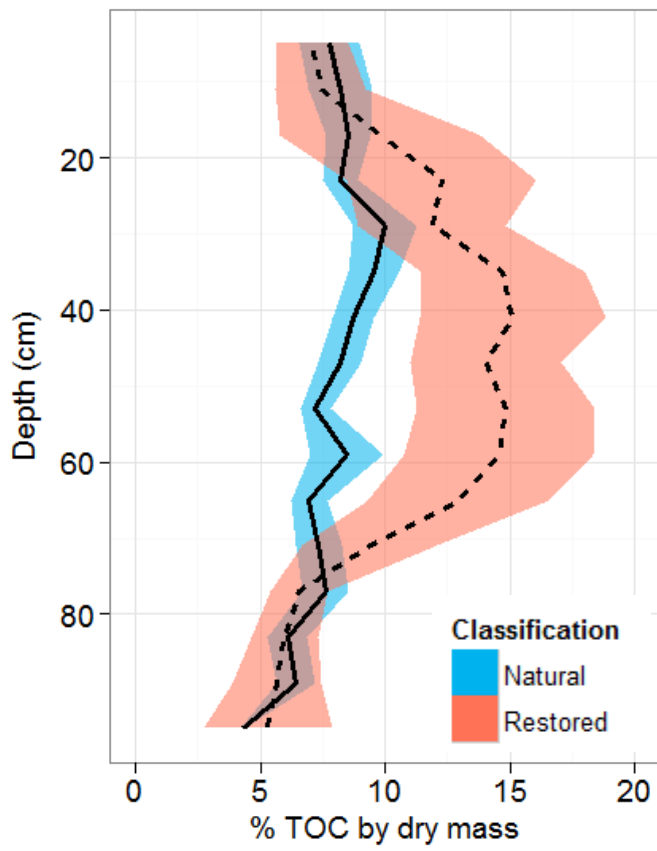
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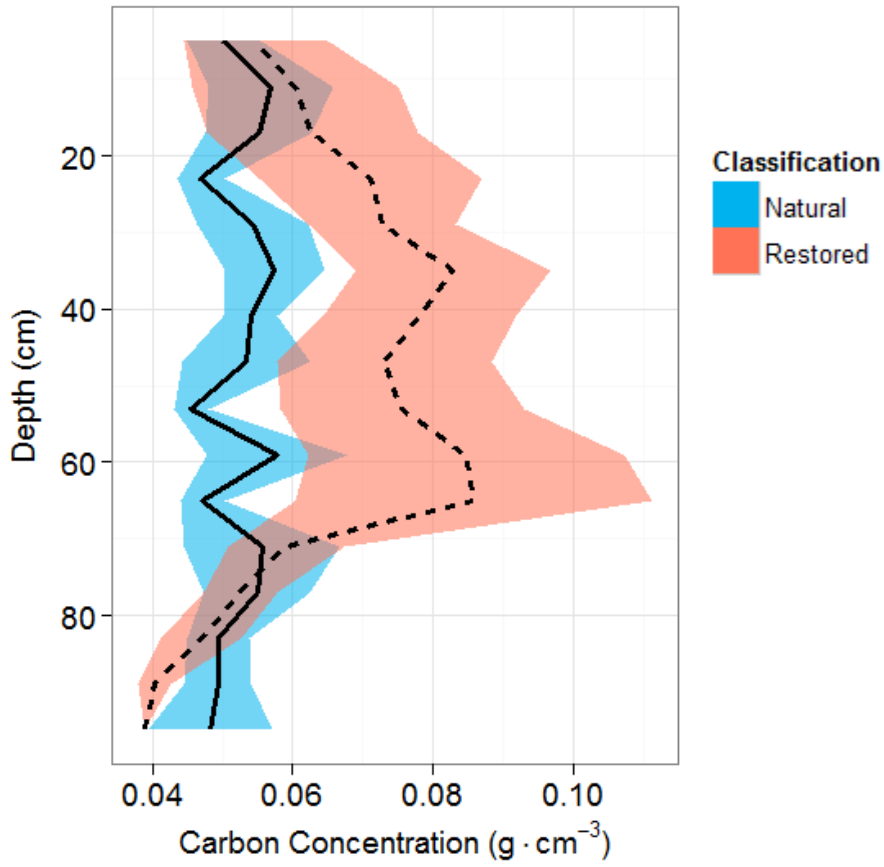


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Figure 6.



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