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Rivett, Skye and Bicknell, Jake E. and Davies, Zoe G. (2016) Effect of reduced-impact logging on seedling recruitment in a neotropical forest. *Forest Ecology and Management*, 367 . pp. 71-79. ISSN 0378-1127.

DOI

<https://doi.org/10.1016/j.foreco.2016.02.022>

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Effect of Reduced-Impact Logging on Seedling Recruitment in a Neotropical Forest

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Abstract

1 Seedling growth and survival are critical for tropical rainforest regeneration. Alterations to natural
2 disturbance regimes, such as those brought about by logging, have the potential to shift relative species
3 abundances and the community composition of forests, resulting in population declines for
4 commercially valuable species. Timber operations therefore need to minimise such changes if long-
5 term sustainability is to be achieved within the industry. Reduced-impact logging (RIL) has been
6 promoted widely as an alternative management strategy to conventional selective logging, as it
7 employs practices that decrease the negative impacts of logging within forests. However, the long-
8 term sustainability of RIL, including the influence it has on the regeneration of species targeted for
9 timber extraction, is still uncertain. Here we undertake a comparative study in Iwokrama forest,
10 Guyana, examining seedling densities of four commercially valuable and two pioneer tree species in
11 unlogged, 1.5 years and 4.5 years postharvest forest plots to ascertain how seedling regeneration is
12 effected by RIL. We find that RIL had either a neutral or positive impact on the density of seedlings
13 of timber species when compared to unlogged forest, with pioneer species densities remaining
14 unaffected. We conclude that the forestry practices associated with RIL have little effect on the natural
15 regeneration rates of key commercially valuable tree species in logged neotropical forests.

16

17 Key words: Guyana, Regeneration, Forest disturbance, RIL, Sustainable forestry, Timber

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25 **1. Introduction**

26 Logging rates throughout the world's tropical rainforests continue to increase (Arets 2005; FAO 2010;
27 Gardner 2010) with approximately 30% of their areal extent designated for timber and non-timber
28 product exploitation (FAO 2010). Indeed, over 40 million hectares are currently allocated to selective
29 logging globally (Asner et al. 2009; Blaser et al. 2011). In tropical forests, seedling growth and survival
30 are driven principally by small-scale disturbance dynamics of canopy gaps (Brokaw 1982; Hartshorn
31 1978; ter Steege et al. 1994; Zagt 1997). When a tree falls, either naturally or through logging, a canopy
32 gap is created of varying size. The resultant gap alters the microclimate (light, moisture, and
33 temperature) of the immediate area, stimulating the growth of any seedlings already present (climax
34 species) or triggering seed germination (pioneer and climax species) (Yamamoto 2000). Changes to
35 natural disturbance regimes, such as those brought about by logging, can thus affect the growth,
36 survival and reproduction rates of plant species (Asner et al. 2004; Boot 1996; Brokaw 1982; de Avila
37 et al. 2015; Fenner 1985; Karsten et al. 2014; Rose 2000; ter Steege & Hammond 2000). Consequently,
38 forest assemblage composition can alter over time, due to species-specific variation in re-establishment
39 following logging (Asner et al. 2004; Karsten et al. 2014; ter Steege et al. 2002) and applied
40 silvicultural practices (de Avila et al. 2015). Low disturbance levels tend to favour slower growing
41 hardwood climax species, resulting in relatively stable forest ecosystems that characterise lowland
42 tropical rainforests. As disturbance levels rise, faster growing, less dense pioneer species tend to
43 dominate (Karsten et al. 2014; ter Steege & Hammond 2000). Therefore, the extent to which rainforest
44 structure and composition are impacted by logging is highly dependent on the intensity of logging,
45 harvest interval, and management practices implemented (Gardner 2010; Waide & Lugo 1992; Zagt
46 1997).

47

48 Reduced-Impact Logging (RIL) was developed to provide a more sustainable alternative to
49 conventional selective logging, whereby the detrimental effects inherent in many traditional forestry

50 operations are minimised (Pinard & Putz 1996; Putz et al. 2008). Although the forestry techniques
51 used under RIL vary from country to country, the aim is to retain forest canopy integrity and species
52 diversity (Edwards et al. 2011; Gibson et al. 2011; Putz et al. 2012), reduce land degradation (Bryan
53 et al. 2010; Dykstra 2002; Dykstra & Heinrich 1992; Dykstra & Heinrich 1996; Jonkers 2002; Putz et
54 al. 2008), and decrease the carbon emissions associated with collateral damage to surrounding
55 vegetation and soil disturbance (Pinard & Putz 1996; Putz et al. 2008), while maintaining a sustained
56 timber supply for future cutting cycles (Putz et al. 2000). Tree inventories are undertaken in order to
57 plan the most efficient and least destructive extraction of logged timber and, in some operations,
58 selected harvest trees have attached vines cut several months prior to removal. The trees are then felled
59 using directional techniques in order to facilitate extraction and minimise stand damage, with logs
60 removed using a skidder and winch.

61

62 In this study, we examine natural regeneration levels of commercially valuable tree species in a RIL
63 logging operation in Guyana. Guyana's commercial timber species occur in isolated stands dominated
64 by one or two species (Johnston & Gillman 1995). Harvesting operations are therefore selective by
65 necessity with extraction rates averaging 2-3 trees/ha⁻¹ (Blaser et al. 2011; Jonkers 2002; van der Hout
66 1999), although they can be as high as 20 trees/ha⁻¹ in some areas (Jonkers 2002). While the countries
67 annual rate of 0.3% deforestation is relatively low compared with other tropical countries (FAO 2006),
68 timber constitutes an important component of the national economy (Blaser et al. 2011; GFC 2002).
69 As in many other tropical countries, Guyana's timber industry relies on natural regeneration
70 (Hammond et al. 1996; van der Hout 1999), meaning that logging that has a detrimental impact on the
71 natural regeneration of commercially important tree species will not be sustainable in the long-term.
72 Historically, the timber industry in the country has centred on *Chlorocardium rodiei* (greenheart), but
73 increased market demand has seen the number of species targeted by logging expand considerably in
74 recent decades (Jonkers 2002).

75

76 Presently, there is a paucity of research into the effects of RIL on natural seedling regeneration within
77 the neotropics (Lobo et al. 2007; Rose 2000), with the majority of studies focusing on the application
78 of silviculture (Dekker & de Graaf 2003; Forget et al. 2001; ter Steege et al. 1994), other forms of
79 logging (Kuusipalo et al. 1996; Pinard et al. 1996), or seedling regeneration in the absence of logging
80 disturbance (Baraloto & Goldberg 2004; Baraloto et al. 2005). Consequently, this paper fills an
81 important gap in our understanding, thus contributing to the improvement of management practices
82 within RIL forest stands and the long-term sustainable use of commercially important target species
83 across their range (Arets 2005; Putz et al. 2000; van der Hout 2000).

84

85 **2. Material and Methods**

86 2.1 Study area

87 Iwokrama forest is located in central Guyana (Fig. 1.), covering an area of 371,000 ha⁻¹. It was
88 established in 1996 as a demonstration site to exemplify how tropical forest exploitation can be
89 sustainable, with commercially viable logging being balanced with biodiversity conservation and local
90 community needs (Watkins 2005). The climate is tropical, with an annual rainfall ~ 3700 mm across
91 two rainy seasons (May-August and December-January). Temperatures range from a mean minimum
92 of 22 °C overnight in July, up to a daytime maximum of 36 °C in October.

93

94 The study area (Fig.1) is characterised by low-lying terra firme tropical rainforest on nutrient poor
95 soils. Dominant forest types include: (i) mixed *C. rodiei*, *Eschweilera* spp. and *Swartzia leiocalycina*
96 forest; (ii) *Mora excelsa*, *Euterpe oleracea*, *Carapa guianensis* and *Pentaclethra macroloba* forest;
97 and, (iii) mixed *C. rodiei*, *Catostemma fragrans*, and *Eperua falcata* forest.

98

99 RIL became operational in Iwokrama forest during 2007, with operations certified by the Forestry
100 Stewardship Council (FSC). Sustainable harvest levels are calculated based on species growth rates
101 combined with a 60-year polycyclic felling rotation. Logging intensity (calculated within a 100 m
102 radius from the sampling sites) ranged from 0.6-11.1 (mean = 3.7, median = 3.2, S.D. = 2.6) trees/ha⁻¹,
103 with an average of 152 m/ha⁻¹ of skid trails throughout the logging concession (Bicknell et al. 2015).

104

105 2.2 Study design

106 A comparative study was undertaken examining seedling density for six species, in both unlogged and
107 postharvest forest stands, to ascertain how RIL influences forest regeneration. Following Rose (2000),
108 we sampled seedlings (defined as up to 150 cm tall) of the four primary timber species logged in the
109 Guianas (Hammond et al. 1996; van der Hout 2000): *C. rodiei* (greenheart), *Dicorynia guianensis*
110 (*basralocus*), *E. falcata* (soft wallaba), and *Goupia glabra* (kabukalli). In addition, we also assessed
111 the densities of the two most common pioneer species, *Cecropia obtusifolia* and *Cecropia*
112 *sciadophylla*, which are indicators of disturbance as they grow along forest edges and within canopy
113 gaps (Alvarez-Buylla & Martinez-Ramos 1992). Seedlings were then assigned to one of three height
114 classes (0-50, 50-100 and 100-150 cm).

115

116 The study was conducted in May and June 2012, within the *C. rodiei*, *Eschweilera* spp. and *S.*
117 *leiocalycina* forest type which is predominant in the Iwokrama logging concession. Two postharvest
118 temporal logging treatments (1.5 and 4.5 years after timber extraction) and unlogged (control) forest
119 were sampled. Sample plots of 20 x 20 m were used to determine seedling densities; this size was large
120 enough for accurate estimates of seedling densities, but not too large to preclude maximum replication
121 of plots per treatment (Bullock 2006). In total, sixty plots were sampled, comprising 20 within each of
122 three harvesting blocks (Fig. 1). The sampling areas had been divided into a 20 x 20 m grid for tree
123 inventory purposes prior to logging. The intersections of the grid were used to assign plot localities,

124 using a random number generator to select coordinates. In logged treatments, the south-west corner of
125 each plot was constrained to within a 50 m radius of a felled tree. This means that we inevitably
126 sampled seedlings both within and on the edge of these gaps. In the unlogged forest, plots were
127 similarly constrained to within a 50 m radius of inventoried trees allocated for felling, with many plots
128 also falling within or adjacent to natural gaps. This was done to ensure a comparable adult community
129 composition between the three treatments. Areas subject to much higher intensity impacts, such as
130 skid trails, roads, mill sites and log landings (where vegetation is highly disturbed or removed), were
131 excluded from sampling. This was so that the focus was on areas that will provide future timber yields,
132 rather than sampling logging infrastructure which is likely to be cleared again during the next round
133 of timber extraction and, thus, where commercially valuable species will not be able to grow to
134 maturity between cutting cycles.

135

136 2.3 Reproductive ecology of six species

137 Whilst the specific reproductive and ecological traits of the species studied vary (summarised in Table
138 1), pioneers tend to have small seeds, which are readily dispersed and grow rapidly in large gaps
139 (Martinez-Ramos et al. 1989; Pons et al. 2005) during the first 1-5 years post germination (Baraloto et
140 al. 2005). Larger seeded climax species targeted for timber harvesting can persist as seedlings for a
141 long time (Forget 1989) within shaded environments, attaining maturity as and when light levels
142 increase (Martinez-Ramos et al. 1989).

143

144 2.4 Data analyses

145 Seedling densities for each species were compared between unlogged and the two temporal logging
146 treatments to determine the effect of RIL on regeneration rates. Seedling densities within the three
147 height classes were also compared across treatments to determine the effects of logging on the
148 recruitment and regeneration of seedlings of different ages. All data were \log_{10} transformed prior to

149 analyses, and non-parametric Kruskal-Wallis tests were employed to examine differences in densities
150 between treatments. Mann-Whitney U tests were used to make post-hoc comparisons. All analyses
151 were conducted in SPSS (IBM v. 19).

152

153 Additionally, community analyses were used to determine if seedling densities differed between
154 treatments for all six species. This was conducted via non-metric multi-dimensional scaling (NMDS),
155 coupled with analysis of similarity (ANOSIM). The NMDS, based on Bray-Curtis dissimilarity
156 coefficients, was implemented in PC-ORD v.6.07 (McClune & Mefford 2011). Five hundred iterations
157 and 250 runs of both real and randomised data were used to produce a final ordination of minimum
158 stress and consisting of two axes. ANOSIM was computed from 999 permutations in R (R Core Team
159 2013).

160

161 **3. Results**

162 In total, 13,771 seedlings of the six target species were sampled across the 60 plots. Of these, 69%
163 were greenheart, 17% soft wallaba, 13% basralocus, and 0.5% kabukalli. The two pioneer *Cecropia*
164 species combined comprised less than 0.5% of the total number of seedlings recorded. Greenheart had
165 the highest seedling densities within both the treatment and control plots, followed by basralocus in
166 unlogged forest, and soft wallaba in the 1.5 and 4.5 years postharvest plots. Both pioneer species were
167 unrecorded in unlogged and 4.5 years postharvest plots (Fig. 2).

168

169 Plots occurring in the 4.5 years postharvest forest treatment contained the highest overall density of
170 seedlings (42% of all seedlings), with unlogged forest (34%) and 1.5 years postharvest forest (24%)
171 containing slightly lower densities (Table 3). Of the six species studied, overall densities of four
172 species (greenheart, basralocus, and both *Cecropia* species) did not differ between the three types of
173 plot (Table 2; Fig. 2). Significant increases in seedling densities of soft wallaba and kabukalli were

174 apparent across the 1.5 years and 4.5 years postharvest forest compared to unlogged forest (Fig. 2;
175 Table 2).

176

177 Within height classes, the seedling densities of soft wallaba were consistently greater in 4.5 years
178 postharvest forest compared to both unlogged and 1.5 years postharvest forest ($p < 0.001$ in all
179 comparisons). Greenheart and *Cecropia obtusifolia* seedling densities were significantly lower in the
180 100–150 cm height class ($p = 0.042$ and $p = 0.045$ respectively), and kabukalli seedling densities
181 were significantly higher in 0–50 cm class ($p = 0.018$). All other species showed no significant
182 differences within height classes across treatments ($p > 0.05$ in all cases) (Tables 2 and 3; Fig. 3).

183

184 The NMDS ordination of community structure represented 62% of the dissimilarity between
185 treatments and control (Fig. 4), and analysis of similarity indicated that significant differences were
186 evident between the 4.5 year plots and all others (ANOSIM - unlogged versus 1.5 year: $R = 0.02$, $p =$
187 0.21 ; unlogged versus 4.5 year: $R = 0.26$, $p < 0.01$; 1.5 year versus 4.5 year: $R = 0.17$, $p < 0.01$). This
188 showed the community composition of the 4.5 year postharvest forest differed from both the 1.5 year
189 postharvest and unlogged forest. However, there was no difference between the community
190 composition of the 1.5 year postharvest plots and unlogged plots.

191

192 **4. Discussion**

193 Species specific biological responses, including regeneration rates and the original density of target
194 species, retention of mature trees for seed dispersal, logging intensity and time between cutting cycles
195 (Baraloto et al. 2005; Polak 1992; Sist et al. 2003, ter Steege & Hammond 2000), are key
196 considerations in determining the long-term sustainability of logging. A failure to integrate such basic
197 ecological information into forest management planning can lead to declines in exploited species
198 populations, alter community composition and threaten future timber yields (Hammond et al. 1996;

199 Shearman et al. 2012; Zimmerman & Kormos 2012). As RIL explicitly takes into account these factors,
200 it is likely to have the least detrimental impact on commercially valuable timber species when
201 compared with conventional selective logging (West et al. 2014).

202

203 Our findings suggest that disturbance arising from RIL operations may not have a lasting negative
204 impact on seedling regeneration and, for some species, may even help to encourage establishment (ter
205 Steege et al. 1994; Rose 2000; ter Steege et al. 2002; Putzel et al. 2011; Karsten et al. 2014). Of the
206 species studied, soft wallaba showed the largest increase in seedling densities across the temporal
207 logging treatments. It is likely that this species drove differences in overall assemblage composition
208 between treatments. Previous research into the growth rate of soft wallaba after logging suggests that
209 the relatively high abundance of seedlings found in our study could subsequently result in a greater
210 abundance of soft wallaba over time, altering the forest assemblage and dynamics in the long-term
211 (Herault et al. 2010). While this may be a desirable outcome for forest management if market demand
212 for this species increases, soft wallaba is already one of the most widespread canopy species in the
213 Guiana's (ter Steege & Zondervan 2000; ter Steege et al. 2013). As such, limiting gap size and
214 minimising disturbance through RIL will be important in maintaining the current tree assemblage
215 composition of the forest (Herault et al. 2010). Without such precautions, this species may outcompete
216 other commercially valuable but less responsive timber species.

217

218 While RIL had no effect on the overall seedling densities of either greenheart or basralocus, greenheart
219 seedling density was greater within the taller height classes following logging, which is probably a
220 response to moderate increases in light levels (ter Steege et al. 1994). Basralocus is also known to be
221 negatively affected by some forms of selective logging (Degen et al. 2006), although no changes to
222 seedling densities for this species across the height classes were observed in this study. Our results

223 indicate, therefore, that disturbance levels following RIL operations remain sufficiently low enough to
224 have little to no impact on the long-term persistence of these species.

225

226 Densities of kabukalli seedlings increased across the logged treatments compared with unlogged
227 forest, indicating regeneration of this species was stimulated by logging disturbance. However,
228 seedling numbers for this species were the lowest of the four timber species surveyed, paralleling more
229 closely with regeneration responses of the two pioneer species, and consistent with the reported
230 regeneration responses of other light preferring species in logged forests (Karsten et al. 2014; Putzel
231 et al. 2011; Rose 2000). The outcome of our study implies that the regeneration potential of kabukalli
232 may be constrained within RIL concessions to outside the extraction forest in areas where disturbance
233 is highest, such as along skid trails, within log landings and mill sites, or where larger gaps open within
234 the forest canopy.

235

236 Neither of the two pioneer species showed a difference in seedling densities between the temporal
237 logging treatments. Recorded numbers of both *Cecropia* species were very low in 1.5 years forest,
238 with none documented in unlogged or 4.5 years postharvest forest plots. This reflects the biology of
239 *Cecropia* species where successful recruitment is restricted to gaps less than three years old and larger
240 than 100 m² (Alvarez-Buylla & Martinez-Ramos 1992; Vazquez-Yanes & Smith 1982) on disturbed
241 mineral soils (Lawton & Putz 1988), dropping off markedly as the canopy closes (Rose 2000). This
242 suggests that structural and soil disturbance within the standing forest area may have been kept to a
243 minimum. However, as skid trails and other logging infrastructure constitute the greatest damage
244 caused by RIL (Asner et al. 2004), additional research within the Guiana's is warranted to determine
245 the full impact of logging on commercially valuable species (Karsten et al. 2014).

246

247 Overall our work demonstrates that disturbance levels following RIL in Iwokrama forest, within the
248 vicinity of logged gaps, is minimal, with regeneration rates of four commercially harvested timber
249 species either unchanged or increasing after logging. As none of the timber species included in this
250 study showed a reduction in density postharvest, it is likely that RIL will allow effective natural
251 regeneration to occur without the need for further silvicultural intervention (Putz et al. 2008).
252 Furthermore, recent research has shown that the community composition of important seed dispersing
253 animals remain relatively unaltered by RIL (e.g. Bicknell & Peres 2010; Bicknell et al. 2014; Bicknell
254 et al. 2015), and thus the important role they play in forest regeneration is likely to be maintained.

255

256 **5. Conclusion**

257 Though arguments remain against the sustainability of logging across the tropics (Shearman et al.
258 2012; Zimmerman & Kormos 2012) the timber industry will undoubtedly persist into the future. As
259 lowland rainforests in the Neotropics, including Guyana, contain a large number of tree species with
260 highly restricted distributions (Gentry 1992), it is crucial that logging has the least detrimental impact
261 possible on the overall integrity of forest ecosystems and exploited species populations. Adjusting
262 harvesting practices to ensure the effective natural regeneration of commercially valuable species is
263 an important step in safeguarding the long-term viability of the industry. The results from this study
264 indicate that RIL may provide a sustainable alternative to other forms of logging, and efforts should
265 be made to implement it more widely to maintain the ecological and economic value of rainforests
266 indefinitely.

267

268 **Acknowledgments**

269 Thanks to R. Thomas, I. Bovolo and V. Welch from Iwokrama International Centre for in-country
270 research assistance, K. Rodney for supplying forestry information, and the Iwokrama rangers for help

271 in the field. We are grateful to the Guyana Environmental Protection Agency for granting research
272 permission.

273

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Table 1: Summary information related to the reproductive ecology of four commercially valuable (CV) and two pioneer (PI) tree species, including seed mass, shade tolerance, primary seed dispersal vectors (u, unassisted; m, mammal; b, bat and/or bird; w, wind and/or water), seed dispersal distance, tree height at maturity and diameter at breast height (DBH) at maturity (Fournier-Origgi 2002; Gerard et al. 1996; Hammond et al. 1996; Horsley et al. 2015; ITTO 2015). Market information for the Iwokrama operations is provided for the four timber tree species, and comprises minimum cutting size (DBH) for logs, and mean annual increments (MAI).

Species	Common name	Species type	Reproductive ecology					Market information		
			Seed Mass ¹ (g)	Shade tolerant Y/N	Seed dispersal vectors	Seed dispersal distance (m)	Height at maturity (m)	DBH at maturity (m)	Minimum cutting DBH (m)*	MAI m ³ /ha/yr ⁻¹ *
<i>Chlorocardium rodiei</i>	Greenheart	CV	65.5±22.3	Y	u/m	30	20-45	0.3-0.6	0.45	0.129
<i>Eperua falcata</i>	Soft wallaba	CV	9.22	Y	u/m	50	15-30	0.6-1	0.5	0.166
<i>Dicorynia guianensis</i>	Basralocus	CV	1.36	Y	u/m	>50	20-45	0.5-1.5	0.5	unknown
<i>Goupia glabra</i>	Kabukalli	CV	0.001	Y	w/b	>100	20-40	0.6-1.5	0.4	0.037
<i>Cecropia obtusifolia</i>	Cecropia	PI	<0.001	N	w/b	>100	10-40	0.2-0.5	-	-
<i>Cecropia sciadophylla</i>	Cecropia	PI	<0.001	N	w/b	>100	10-40	0.2-0.5	-	-

¹ Fresh seed weight for *Chlorocardium rodiei*, *Eperua falcata*, and *Dicorynia guianensis*. Dry seed weight *Goupia glabra*, *Cecropia obtusifolia*, and *Cecropia sciadophylla*. (de Grandcourt et al. 2004; Rose 2000; ter Steege 1990).

* In Iwokrama Forest, Guyana

Table 2: Comparison of seedling densities between 1.5 year and 4.5 year postharvest logging treatment and control (unlogged) plots, using Kruskal-Wallis and Mann-Whitney U post-hoc tests, for four commercially valuable (CV) and two pioneer (PI) tree species.

Species name	Common name	Species type	Seedling density			Post-hoc comparison					
						1.5 years vs. Unlogged		4.5 years vs. Unlogged		1.5 years vs. 4.5 years	
			X ²	df	p	U	p	U	p	U	p
<i>Chlorocardium rodiei</i>	Greenheart	CV	2.7	2	0.25	149.0	0.17	181.5	0.62	147.5	0.16
<i>Eperua falcata</i>	Soft wallaba	CV	20.5	2	<0.001	184.5	0.65	45.0	<0.001	73.5	<0.001
<i>Dicorynia guianensis</i>	Basralocus	CV	1.7	2	0.42	166.5	0.36	155.0	0.22	181.5	0.61
<i>Goupia glabra</i>	Kabukalli	CV	10.5	2	<0.01	121.0	<0.05	98.0	<0.01	180.0	0.57
<i>Cecropia obtusifolia</i>	Cecropia	PI	6.2	2	<0.05	170.0	0.08	N/A	N/A	170.0	0.08
<i>Cecropia sciadophylla</i>	Cecropia	PI	4.1	2	0.13	180.0	0.15	N/A	N/A	180.0	0.15

Table 3: Mean seedling densities per hectare for each species within three height classes (0-50, 50-100 and 100-150 cm) across unlogged and 1.5 year and 4.5 year postharvest logging plots. One decimal place is provided where densities are <1 seedling per hectare.

Height class	Species		Mean density (seedlings/ha ⁻¹)		
			Plot type		
			Unlogged	1.5 years	4.5 years
0-50	Chlorocardium rodiei	Greenheart	476	198	422
	Eperua falcata	Soft wallaba	17	127	303
	Dicorynia guianensis	Basralocus	228	60	133
	Goupia glabra	Kabukalli	0.5	8	5
	Cecropia obtusifolia	Cecropia	0	0.5	0
	Cecropia sciadophylla	Cecropia	0	0.3	0
50-100	Chlorocardium rodiei	Greenheart	405	372	460
	Eperua falcata	Soft wallaba	14	15	88
	Dicorynia guianensis	Basralocus	7	7	7
	Goupia glabra	Kabukalli	0	1	1
	Cecropia obtusifolia	Cecropia	0	1	0
	Cecropia sciadophylla	Cecropia	0	0	0
100-150	Chlorocardium rodiei	Greenheart	10	22	24
	Eperua falcata	Soft wallaba	3	4	18
	Dicorynia guianensis	Basralocus	1	2	0.3
	Goupia glabra	Kabukalli	0	0.8	1
	Cecropia obtusifolia	Cecropia	0	0.8	0
	Cecropia sciadophylla	Cecropia	0	0.3	0
All height classes combined	Chlorocardium rodiei	Greenheart	891	592	906
	Eperua falcata	Soft wallaba	34	146	409
	Dicorynia guianensis	Basralocus	236	68	140
	Goupia glabra	Kabukalli	0.8	10	7
	Cecropia obtusifolia	Cecropia	0	3	0
	Cecropia sciadophylla	Cecropia	0	0.5	0

Figure legends

Figure 1. The location of the study area in Iwokrama forest, Guyana, South America. The Reduced-Impact Logging 1.5 and 4.5 year postharvest treatment plots are indicated by dark grey and black squares respectively. Unlogged forest plots are shown as light grey squares. Logging roads and skid trails (dashed lines) are shown within logged forest to indicate the level of logging disturbance. Inset: The location of Iwokrama forest (shaded grey) within Guyana.

Figure 2. Box plots showing median \log_{10} densities of seedlings for four commercially valuable timber and two pioneer tree species, across 20 unlogged, Reduced-Impact Logging (RIL) 1.5 years postharvest and RIL 4.5 years postharvest treatment plots: (a) *Chlorocardium rodiei* (greenheart); (b) *Dicorynia guianensis* (basralocus); (c) *Eperua falcata* (soft wallaba); (d) *Goupia glabra* (kabukalli); (e) *Cecropia obtusifolia*; and, (f) *Cecropia sciadophylla*. Thick horizontal lines indicate median values, the boxes show the interquartile range, and the vertical lines specify either the maximum value or 1.5 times the interquartile range (whichever is smaller), ° indicates a moderate outlier and * an extreme outlier. Associated statistics are given in Table 2.

Figure 3. Box plots showing median \log_{10} densities of seedlings for four commercially valuable timber and two pioneer tree species, across 20 unlogged, Reduced-Impact Logging (RIL) 1.5 years postharvest and RIL 4.5 years postharvest treatment plots, within three height classes (0-50, 50-100 and 100-150 cm): (a) *Chlorocardium rodiei* (greenheart); (b) *Dicorynia guianensis* (basralocus); (c) *Eperua falcata* (soft wallaba); (d) *Goupia glabra* (kabukalli); (e) *Cecropia obtusifolia*; and, (f) *Cecropia sciadophylla*. Dark grey boxes are for 0-50 cm, light grey boxes for 50-100 cm and white boxes for 100-150 cm height classes. Thick horizontal lines indicate median values, the boxes show the interquartile range, and the vertical lines specify either the maximum value or 1.5 times the

interquartile range of the data (whichever is smaller), ° indicates a moderate outlier and * an extreme outlier. Associated statistics are given in the results text.

Figure 4. Non-metric multidimensional scaling (NMDS) ordination of seedling community structure across the two Reduced-Impact Logging (RIL) treatment and unlogged forest plots: white, unlogged; grey, RIL 1.5 year postharvest; black, RIL 4.5 years postharvest. The first NMDS axis explains 27% of the variation, and the second axis 35%. Stress = 0.15.

Figure 1

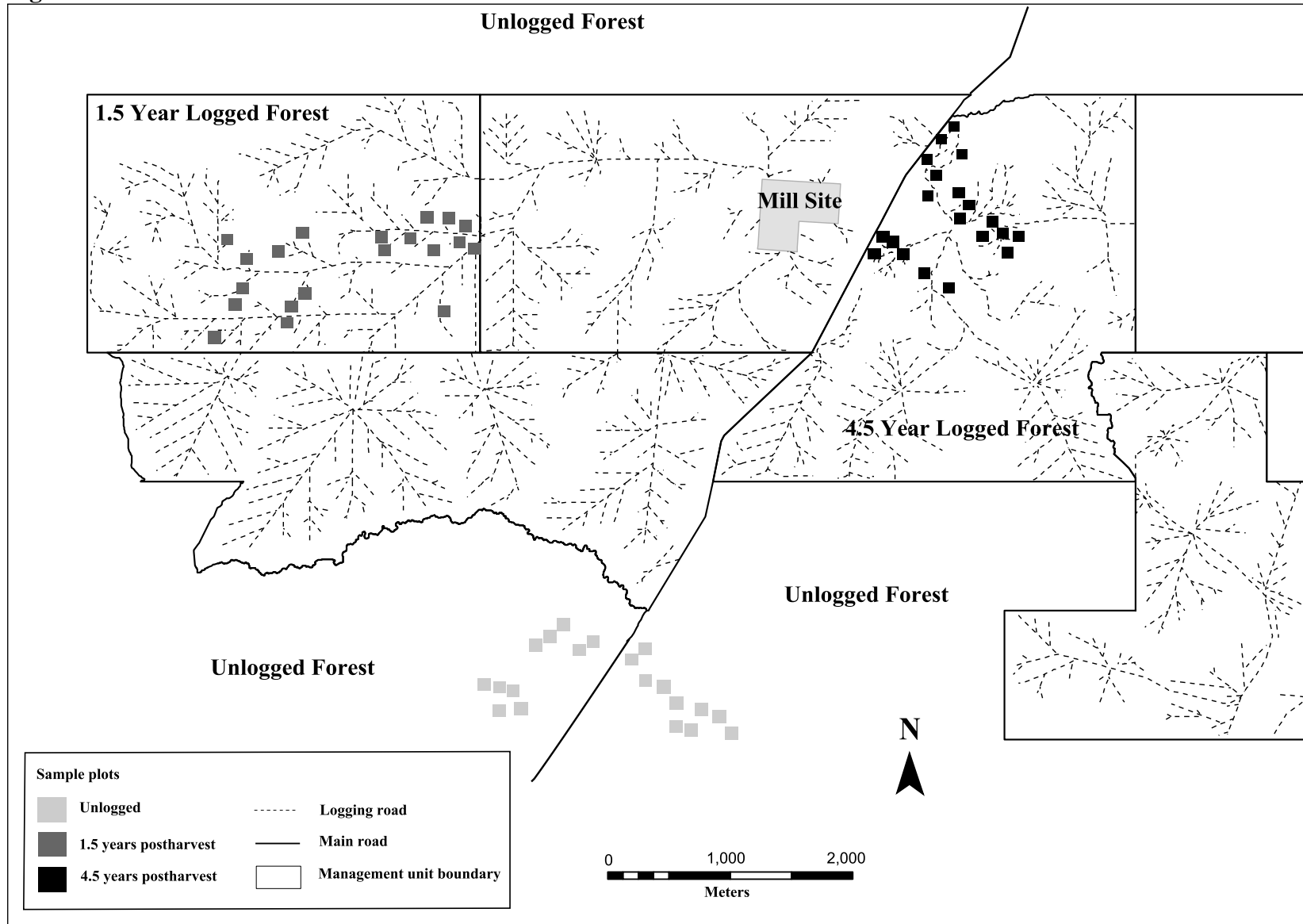


Figure 2

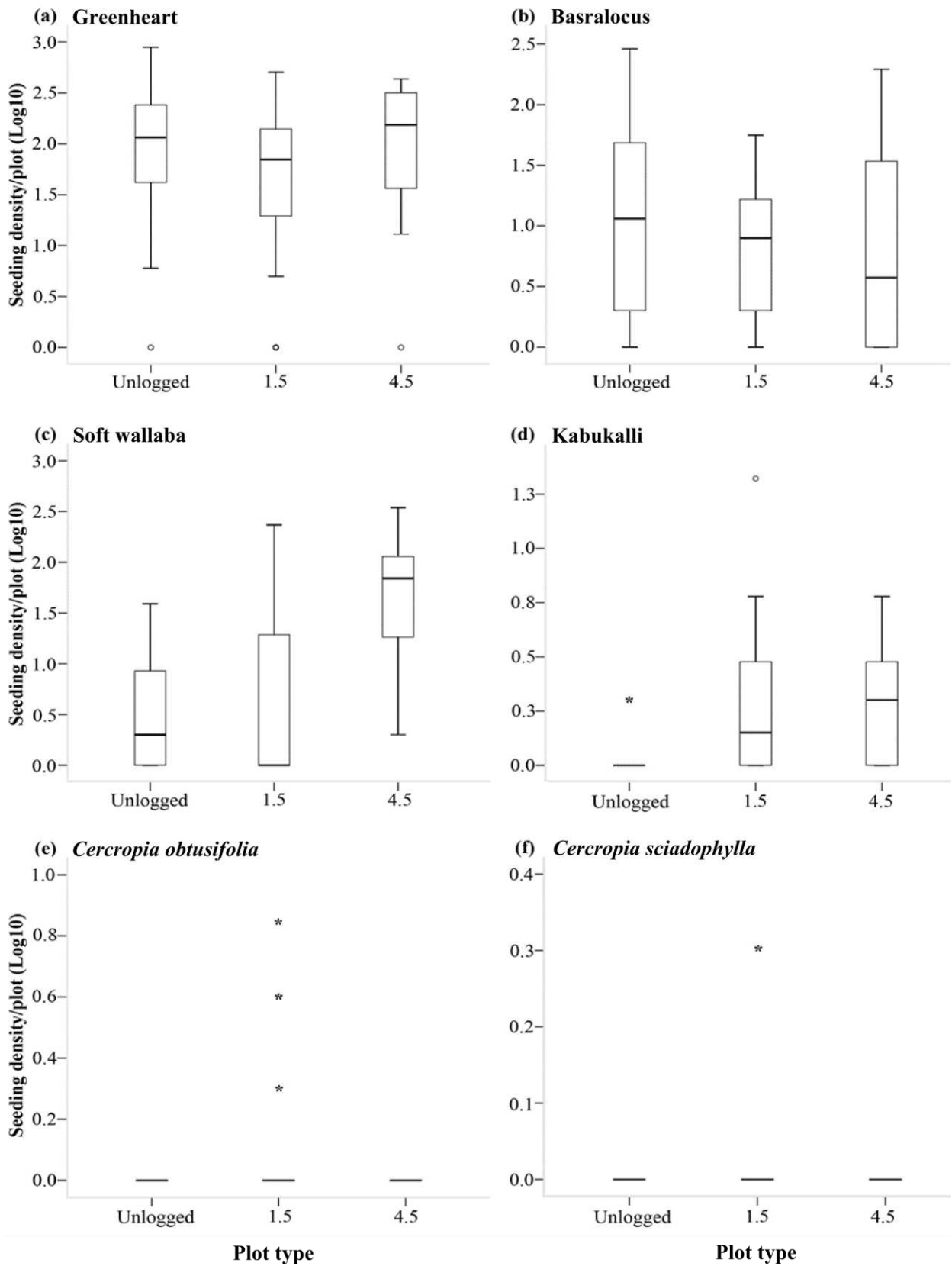


Figure 3

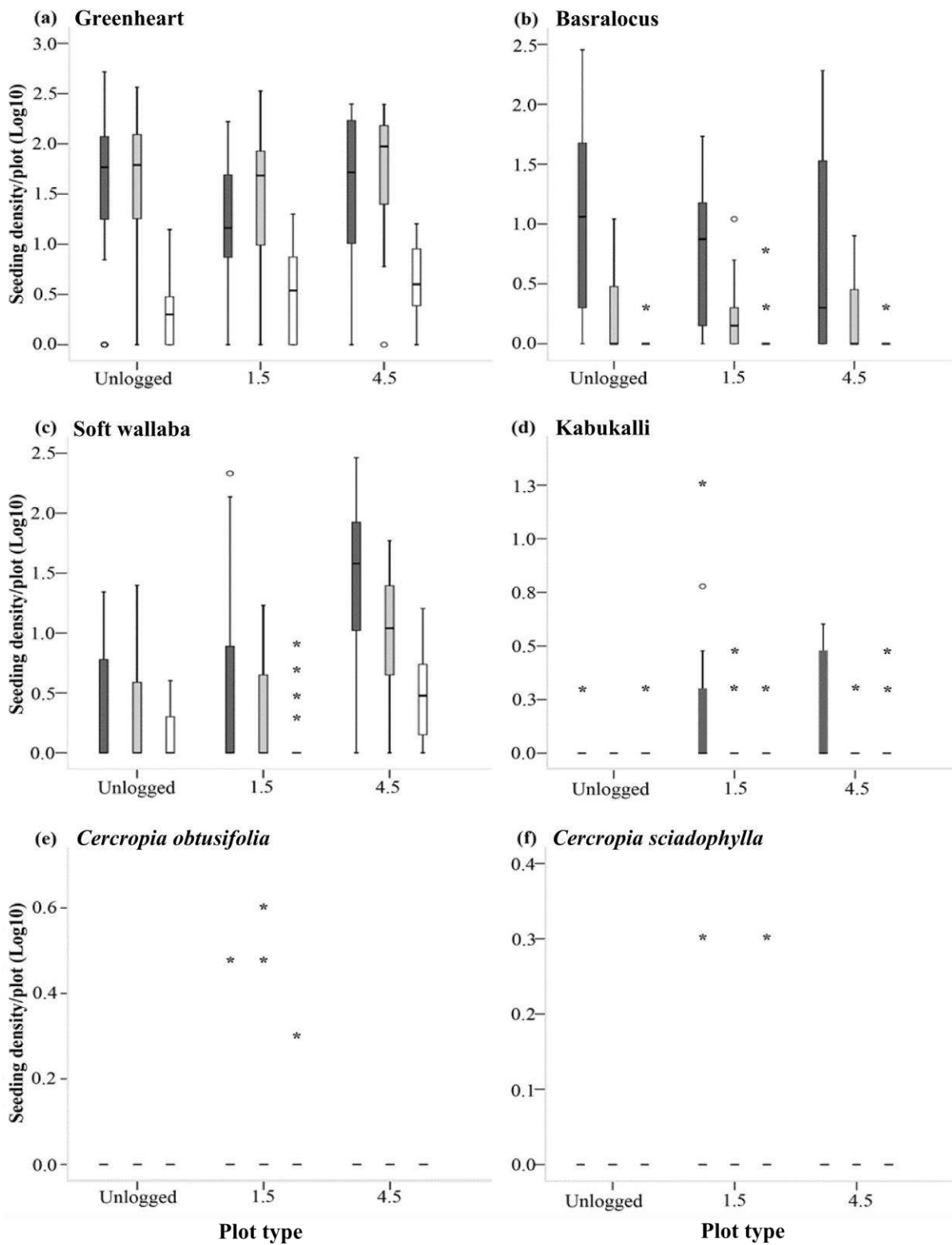


Figure 4

