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Visual detection based distance sampling offers efficient density estimation for distinctive low abundance tropical forest tree species in complex terrain

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2 **Visual detection based distance sampling offers efficient density estimation for**
3 **distinctive low abundance tropical forest tree species in complex terrain**

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13

14 **Abstract**

15 Good density estimates for low abundance tree species are costly to achieve
16 especially in rugged or disturbed forest landscapes. More efficient methods would be of
17 considerable value to managers and conservationists. Here we assess a method that has been
18 neglected in this context. We examine and compare distance-based visual detection line-
19 transects and conventional fixed-width transects for assessing a distinctive low abundance
20 species of conservation significance, *Myrianthus holstii* Engl., in three separate areas, within
21 a steep, disturbed mountain rain forest. Precision and implied accuracy appeared
22 substantially better with the visual detection line-transect than with the fixed-width transect
23 for equivalent costs and effort at all three landscapes but as the two methods provide
24 different estimates there are questions of possible bias in both approaches. We discuss the
25 strengths and weakness of the distance approach and suggest some recommendations
26 concerning its application. We conclude that the distance method is suited to low density
27 species that are easily identified, even when understorey vegetation and terrain severely
28 impair visibility. However, due to the differences in detection probabilities, populations
29 need to be stratified both by tree size and context.

30 **Keywords:** bias, detection, efficient-rain-forest-survey, inventory, method-selection, rapid-
31 biodiversity-assessment.

32

33 **1.0 Introduction**

34 Information on plant species densities is helpful for effective forest management (Wong
35 2000). Such evaluations are a key part of classical forest inventories and associated
36 sampling theory. But when species are rare, as they typically are in tropical forests, these
37 methods are expensive to apply with satisfactory accuracy.

38 Various approaches have been suggested to offer more cost-effective means to assess
39 low abundance species. We require approaches that minimise bias and maximise precision
40 for the least amount of field effort and expense (Scott & Gove 2002). Fixed area plot
41 approaches such as belt-transect are commonly used to survey tree species (Philip 1994).
42 These have the advantages of good coverage of habitat heterogeneity and ease of
43 implementation (DeWalt *et al.* 2003, Hashimoto *et al.* 2003). Various distance based
44 sampling methods have been used in plant ecology: these include the plot-less approaches
45 that utilise distance measurements from points to the nearest trees, or from trees to their
46 nearest neighbours (e.g. Cottam and Curtis 1956, Pielou, 1977), but such approaches are
47 generally less useful for accurate density estimates.

48 Novel approaches continue to be advanced: e.g., adaptive cluster sampling (Thompson
49 1992) and size-limited variable area plots (Sheil *et al.* 2003). The visual detection line-
50 transect method (“distance” in the rest of this paper) is already popular in estimating animal
51 species densities due to its demonstrated efficiency and practicability (Buckland *et al.*,
52 2000). This distance approach has gained little attention for the assessment of vegetation
53 including forest trees. The reasons for this neglect are unclear but likely include low
54 awareness as most texts on the methods emphasise animals and are targeted at zoologists.
55 Here we assess one form of this approach, line transects, and compare it with a belt (fixed
56 width) transect, for the assessment of a distinctive, low abundance species, *Myrianthus*
57 *holstii* Engl., in the Bwindi Impenetrable National Park and World Heritage Site, in South-
58 western Uganda.

59 The efficiency of any new method should be evaluated for reliability in varying
60 conditions in comparison with the best alternative methods (Hounscome *et al.*, 2005). Here

61 we compare the distance sampling method and belt-transect method for estimating the
62 density of single tree species. We also evaluate the bias, precision and cost of generating
63 data using the two methods under varying conditions.

64

65 **2.0 Materials and Methods**

66 **2.1 Study area**

67 Our study was conducted in three areas or landscapes with different forest characteristics
68 and altitudinal contexts (A, B, C) in Bwindi Impenetrable National Park (0°53′-1°8′S and
69 29°35′-29°50′E) between October 2009 and April 2010 (Fig. 1). Bwindi was managed as a
70 production forest reserve from 1942 until in 1991 when it was gazetted as a national park. It
71 covers an area of 331 km² at an altitude of 1160 to 2607 m above sea level (a.s.l.), and has a
72 rugged, undulating topography. The vegetation is classified as “medium altitude moist
73 evergreen forest” and “high altitude sub-montane forest” (Langdale-Brown *et al.*, 1964).
74 The climate in Bwindi is equatorial with two rainfall peaks, from March to May and
75 September to November, with annual mean rainfall of 1525 mm, and an annual mean
76 temperature of 18.35° (<http://www.itfc.org>, 20/10/2010).

77 Landscape A (Buhoma) is located on the western section of the park between 1550 and
78 1850 m a.s.l. and consists predominantly of secondary and mixed forest, with an understorey
79 of *Mimulopsis* spp. and ferns on steep slopes. Landscape B (Rushaga) is located in the south
80 between 1805 and 2250 m a.s.l. with open areas and mixed forests, with mixed *Mimulopsis*
81 spp. *Alchornea hirtella* and spiny *Rubus* spp., understorey and steep slopes. Landscape C
82 (Ruhija) is located in the east between 2100 and 2500 m a.s.l. with open forest and scanty
83 mature forest with dense *Mimulopsis solmsii* and *M. arborea*, *Alchornea hirtella* and fern
84 (*Pteridium aquilinum*) and very steep slopes.

85

86 **2.2. Study species**

87 *Myrianthus holstii* Engl. [family (Cecropiaceae) Urticaceae] is a dioecious medium-
88 sized deciduous tree that can grow up to 20 m high. The foliage of *M. holstii* trees are
89 consumed by various of Bwindi’s larger herbivores including the endangered Mountain
90 gorillas (*Gorilla beringei beringei*) and elephants (*Loxodonta africana*) while the tree’s

91 fruits are sought by gorillas and various other frugivores including chimpanzees (*Pan*
92 *troglodytes schweinfurthi*) as well as by humans (Cunningham 1992, Elgart-Berry 2004,
93 Robbins & McNeilage 2003). *Myrianthus holstii* has indeed been judged the “most
94 important gorilla fruit species” with seeds being present in 20% of gorilla fecal samples (and
95 4% of chimpanzee fecal samples) (Stanford & Nkurunungi 2003). Because of this perceived
96 importance to high value endangered wildlife local people have not been permitted access
97 *Myrianthus* fruit inside the National Park by the park authorities (the Uganda Wildlife
98 Authority) despite numerous requests from local communities (Robert Bitariho pers. comm.
99 June 2011).

100 *Myrianthus holstii* occurs in sub-montane and montane forests across Central and East
101 Africa (Iversen, 1991). The palmate leaves are dark green above and pale grey-green below
102 with conspicuous venation. This species is relatively distinctive in the context of Bwindi,
103 since few other species possess large palmate leaves, and of those that do, only *M. holstii*
104 possesses leaves with such a toothed margin. The species is therefore readily recognised at a
105 distance.

106

107 **2.3. Sampling procedure and data analysis**

108 **2.3.1 Methods and enumeration**

109 The *M. holstii* trees (height > 1.3 m) were categorized into four sub-populations based
110 on tree diameter at 1.3m (Dbh) i.e. seedlings (Dbh ≤ 2.5 cm), saplings (Dbh > 2.5 cm but ≤
111 5.0 cm), small adults (Dbh > 5.0 cm but ≤ 10.0 cm) and large adults (Dbh > 10.0 cm). We
112 used two sampling procedures i.e. the conventional belt-transect approach, with a width of
113 10 m (5m to either side of the center line) and a distance based visual detection line-transect
114 (Buckland *et al.* 2000). Each of the three landscapes were surveyed using eight horizontal
115 transects of exactly two kilometers running in a north-south direction from the forest
116 boundary into the interior. We generated random numbers and the first transect was
117 randomly placed (selecting a location and using a random number offset) with the other
118 seven placed systematically 700 m apart. Along each transect, *M. holstii* trees were searched
119 for by one assigned observer moving along the transect centre line. The horizontal
120 perpendicular distance along the transect, and the horizontal perpendicular distance from the
121 transect to each *M. holstii* tree sighted (height > 1.3 m) were recorded. Diameter
122 measurements were taken at 1.3 m above the ground from the upper side of the slope using

123 vernier caliper for seedlings and a diameter tape for saplings and adults. Multi-stemmed
124 trees were considered as one individual by assigning a diameter equivalent to a hypothetical
125 single stem with a sum cross-sectional area equal to the sum of the individual stems. The
126 heights of trees between 1.3 m and 2.5 m tall were measured by tape, while taller stems were
127 calculated from clinometer measurements.

128

129 **2.3.2 Data analysis**

130 For the belt-transect method, the density (D) of *M. holstii* trees was estimated using the
131 equation $D = N/A$ where N = total number of trees recorded and A = total areas of transect
132 in hectares, i.e. $W \times L$, where W and L are total width and length respectively. For the
133 distance method, density was estimated using DISTANCE 6.1 Release 2 Software. This
134 estimates density using the basic equation, $D = N/Pa \times 1/2WL$ (Buckland *et al.*, 2000) where
135 N , W , L are as above, and Pa = the estimated probability of observing an object within a
136 defined area.

137 ‘Distance analysis followed the standard guidelines for DISTANCE software (Anderson
138 & Southwell 1995, Buckland *et al.*, 2000, 2004). Four model types (half-normal, hazard-
139 rate, uniform and negative-exponential), each with cosine, simple polynomial and hermite
140 polynomial adjustments, were fitted to each sub-population in each area surveyed. The data
141 were first right-truncated to eliminate outliers. Data grouped in the correct distance interval
142 based on inspection of the detection frequency histograms. These procedures are all adjusted
143 and judged based on standard procedures in DISTANCE (Anderson & Southwell, 1985,
144 Southwell, 2006). Selection of the most appropriate detection function was based on the
145 minimum Akaike Information Criterion (AIC) (Akaike 1973, Burnham & Anderson 2002).
146 Goodness of fit was tested by chi-square, and variance estimated using a post-stratification
147 variance estimator (Fewster *et al.* 2009).’

148 Detection functions can vary with conditions and were thus selected separately for the
149 three landscapes. To assess possible bias between the estimates of the two methods, percent
150 relative bias (PRB) was used. The $PRB = (D_{strip} - D_{line}) / D_{line} \times 100 \%$ (Ogutu *et al.*, 2006)
151 where D_{strip} is the density estimated by belt-transect method and D_{line} is the density estimated
152 by visual detection line-transect sampling. The precision of the two methods was also
153 compared using the percent coefficient of variance ($\% CV = \{\text{standard error/density}\} \times 100$)
154 where a lower coefficient of variance indicates greater precision (Boulanger *et al.*, 2005).

155 The efficiency of the methods was compared based on number of transects, trees
156 recorded and man-hours. To adjust for unequal effort we compare the implied precision of

157 the two methods as a function of effort as follows: each approach provides a 95%
158 confidence interval (CI) for the density estimate in each of the three landscapes. In each case
159 we know the number of transects, stems recorded and man hours required. We assume that
160 number of transects, stems recorded and man hours can be considered a linear function of
161 each other (i.e. on average double the effort gives double the number of transects and double
162 the number of stems). We know from basic sampling theory that $CI \propto 1/\sqrt{n}$ where n is
163 number of observations and we assume that such a relationship also applies to the distance
164 approach. This allows us to assume that the $CI \propto 1/\sqrt{(\text{number of transects})} \propto 1/\sqrt{(\text{stems})} \propto$
165 $1/\sqrt{(\text{man hours})}$. This allows us to compare results by CI, and relative CI (that is CI/density),
166 in terms of transects, stems and man hours.

167

168 2.4 Results

169 The belt-transect method covered a total area of 16 ha per landscape. Total transect
170 length was 16 km per landscape for both methods. The total number of *M. holstii* trees
171 (height ≥ 1.3 m tall) recorded by the belt-transect method was 494 stems and the distance
172 method was 1438 stems. It took 181.5 hours to survey 24 transects using the belt-transect
173 method and 301.71 hours using the distance method.

174

175 2.4.1 Selection of best Distance model

176 DISTANCE software enables the user to select from one of four basic detection functions
177 (Southwell, 2006). The *Half-normal model* (with Cosine series adjustment) was found most
178 suitable for most sub-populations, as judged by low AIC and high goodness of fit (GoF)
179 (Table 1). The *Negative exponential model* in contrast always gave a much higher AIC value
180 and also yielded markedly higher tree density estimates compared to the other detection
181 functions, indicating likely bias.

182 Is it necessary to use different distance estimation models in the different landscapes? In
183 Distance sampling it is assumed that the detection probability (p) is 1.00 on the transect line
184 but declines with perpendicular distance. We examined whether detection is the same for the
185 different size-classes among landscapes and the likely bias in the estimates as result of
186 detection probability. Detection probability for seedlings, saplings, small adults and large
187 adults were higher in landscape C, followed by B and lowest at A (Table 1). The selected
188 detection function curves had wider shoulders and declined less rapidly at landscape C

189 compared to A and B (Figure 2). For instance, detection probabilities for combined tree
190 populations dropped from 1.0 – 0.1 before 25 m in landscape A and B while at C detection
191 probability dropped from 1.0 – 0.1 after 35 m.

192

193 **2.4.2 Bias**

194 The density estimates obtained from the distance method were consistently higher
195 than those from the belt-transect (Table 1). The probability of this occurring by chance if
196 neither method were biased (or bias were equal) is $(\frac{1}{2})^{12}$, $p = 0.000244$, strongly suggesting
197 that at least one of the approaches is biased. We note that the discrepancy was greatest for
198 seedlings and saplings in landscape A and B respectively (Table 2). Given the dense
199 understory undergrowth in some of these landscapes we believe that the most likely
200 explanation is that the 10 m wide belt transect is subject to errors of omission – this is also
201 indicated by the detection functions from the Distance approach which show a marked drop
202 below 1.0 even within the first 5 m – especially for the shortest stature populations
203 (seedlings and saplings) (figure 2).

204 Another possible source of bias can be investigated by considering whether the
205 combined estimates for subpopulations is the same as that where the subpopulations are
206 pooled prior to estimating the density. With the belt-transect method, the sum of sub-
207 populations density estimates is necessarily equal to the combined population density
208 estimate. In contrast, for the distance approach, the sum of sub-populations yielded
209 consistently higher estimates than the total population (combined size-class) estimates at all
210 the landscapes (Table 1). This difference is 12.67, 25.15 and 27.56 % for the landscapes A,
211 B, and C respectively.

212

213 **2.4.4 Effort and relative efficiency**

214 The distance method approach had lower percent coefficient of variation (% CV)
215 compared to the belt-transect method for all populations (Table 2). This means the distance
216 method approach provided better precision as indicated by very low values of % CV for the
217 estimated densities of the different tree populations – but it also took more time per transect.
218 The Distance approach generally required 50 to 70% more time to complete a transect, but
219 generally involved measuring many more trees: with 2.7, 2.9 and 3.5 times more for
220 landscapes A, B and C respectively (Table 3). The cost of locating and measuring a tree

221 (trees per man hour) is lower using the distance method compared to the belt-transect
222 method at all the study landscapes (Table 3).

223 Comparing the relationship of estimated confidence intervals for density against
224 effort (number of transects, trees and man-hours) for the three landscapes shows that while
225 the differences vary considerably with local conditions the distance method is consistently
226 more precise in both absolute and relative terms than the belt-transect method for nearly all
227 measures of effort (Fig.3a-f). An exception is landscape A, considered on a per stem basis
228 (Fig, 3b).

229

230 **2.5 Discussion**

231 **2.5.1 Suitability for rain forest conditions**

232 Our study appears to be among the first applications of the Distance approach to tropical
233 rain forest trees – though there has been some application to plant populations e.g. cowslips
234 (*Primula scotica* and *P.veris*) in Scotland, by Shewry et al. 2002 and Buckland *et al.* 2007,
235 and six understorey tree species in China, by Chen *et al* 2009). We have found only two
236 other applications to rain forest trees: one concerned the quantification of fruiting species in
237 unlogged and logged forests in New Guinea (Marsden & Pilgrim 2003) while the other
238 involved a modified application for the selection of *Milicia excelsa* Welw. C.C. Berg. trees
239 for morphological comparisons in Benin (Ouinsavi & Sokpon 2010). Our study thus
240 appears to be the first rain forest application seeking to simply estimate stem densities for a
241 given species.

242 The ability to search large areas with relatively limited cost even under demanding field
243 conditions is desirable and, as we shall discuss in greater detail below, relative accuracy and
244 efficiency suggests that the method has wide applicability in assessing rain forest trees –.
245 Though the analytical steps required by the Distance approach are statistically sophisticated,
246 the use of the software meant that model selection, and the resulting density estimation,
247 proved reasonably simple.

248

249 **2.5.2 Variation in detectability**

250 *Myrianthus holstii* is a distinctive tree species: it is reasonably easy to detect even at
251 considerable distances as long as visibility allows. Thick undergrowth and steep terrain
252 influence such visibility. The fitted detection functions (Fig.2) indicate how visibility varied
253 among subpopulations and landscapes. As would be expected larger trees are detected with
254 greater probability at extended distances than are smaller stems. The higher detection of all

255 populations (Table 1) and the wider shoulder of the detection function curves at landscape C
256 compared to B and A (Fig.2) reflects differences in vegetation and terrain and associated
257 visibility. Other studies have found that detection varies with plant height and distinctive
258 morphology (conspicuous flowers and distinctive fruits, Chen *et al* (2009). Similar
259 observations have been made for animals: e.g., Shorrocks *et al* (2008) found that dik-dik are
260 much more easily detected in areas with short than tall grasses which influences the
261 detection functions. Species that are less conspicuous or harder to distinguish would require
262 additional effort and skill. The major difference among landscapes suggests a need for
263 stratification over large-scale surveys over heterogeneous areas when population abundance
264 and visibility may co-vary (finer scale co-variation is a lesser concern and remains a focus of
265 theoretical consideration and development for animal detection, e.g. Ramsey and Harrison
266 2004, Royle et al. 2004).

267

268 **2.5.3 Biases**

269 Our results show that the distance based density estimates were consistently higher than
270 those from the belt transects. Distance methods can overestimate densities if perpendicular
271 distances are not actually perpendicular (Marshall *et al.*, 2008). We minimized this bias by
272 using a compass to fix perpendicular distance – and note that errors of judgment that may be
273 associated with moving animals are avoided with fixed location trees. Under-estimation in
274 the belt transect can result from failure to count all the individuals (Burnham *et al.*, 1985).

275 Our initial assumption was that the 10 m width belt-transect method was unbiased and
276 would provide a reference for the distance estimates. Our field experiences forced us to
277 revise this view. Although considerable effort was made to ensure complete census within
278 the belt-transect, the dense undergrowth/climbers, difficult terrain and animal damage likely
279 allowed some underestimation of smaller stems that may have been hidden in the thick
280 vegetation. These results are consistent with many other vegetation studies indicating that
281 incomplete detection of plants is common in field studies, even under reasonably benign
282 field conditions (Chen et al. 2009, Moore et al. 2011). In our study poor detection is
283 consistent with the larger discrepancy being associated with smaller stems and was most
284 marked where the understorey is dense and where trees were broken (*M. holstii* is often
285 broken by elephants, gorillas and other animals). Of course such errors can be reduced by
286 increased effort: for example if transects were surveyed by multiple observers (e.g. five in
287 line spaced 2m apart). However, the distance approach addresses such bias directly by
288 assuming a detection probability that declines with distance (Buckland *et al.*, 2000 & 2004).

289 Similar results have been reported in animal studies: e.g., Ogotu *et al* (2006) and Shorrocks
290 *et al* (2008) who found distance methods provided higher density estimates than belt-
291 transect approach when applied to African grassland herbivores.

292 We believe that detection probabilities along the central transect line are
293 indistinguishable from 100%. Violation of this assumption would cause underestimation.
294 Such conditions could arise in assessing short plants in a tall dense thicket understorey.
295 Such conditions require specific methods to ensure detection such as careful destructive
296 clearing of the center line or more selective sampling to estimate the degree of under-
297 detection.

298 Nonetheless we do not believe that our application of the distance approach is wholly
299 unbiased. The summed density of sub-populations appears to differ in a relatively consistent
300 manner from estimates based on the total (combined) population (Table 1). According to
301 Buckland *et al* (2004) the ‘pooling robustness’ property of Conventional distance sampling
302 (CDS) method estimators ensures that moderate amounts of unmodeled heterogeneity do not
303 contribute much bias. Nonetheless we are surprised that biases are not greater, considering
304 the variation in visibility of the various sub-populations and the different impact this must
305 have on detection. We are not sure which estimates are most accurate but expect that adding
306 subpopulations reduces some of the size-dependent influences that may otherwise be
307 operating. We speculate that analytical methods might allow even more efficient (and less
308 biased) estimators if information on detection probabilities could be directly modeled as a
309 function of stem-size thus utilizing information lost in the current approach.

310

311 **2.5.3 Efficiency as determined by the two methods**

312 The distance method achieved better precision than the belt-transect in all three
313 landscapes for all the populations (Table 2). The low % CV produced by the distance
314 method approaches compared to the belt-transect method for all the population indicates the
315 improved ability of the distance model approach to minimize standard error. The low
316 abundance of *M. holstii* contributes to a high standard error due to large variance but the
317 distance approach minimizes standard errors better than the belt-transect method since it
318 utilizes the additional information derived from more stem observations and the fitted
319 detection function. Bias can still arise with the distance method, especially if the sample size
320 is small, due to uncertainties when selecting the best model (Buckland, *et al.*, 2000).

321 For the belt method the estimated precision has a fairly predictable relationship with
322 stem density and stem number – the relationship for the distance method is more complex.

323 Buckland, *et al* (2000) suggested that to model detection functions, a minimum of thirty
324 observations are required from a sampled area. Marshall *et al* (2008) found that 60 – 80
325 observations are required to accurately model detection functions. Our analysis using
326 distance method approaches yielded precisions between orders of 4.50 – 14.67 % providing
327 a reliable estimate for future monitoring (see Plumptre, 2000).

328 If the goal is to estimate density and or record stem properties the distance method is
329 more efficient than the belt-transect method because more precise estimates and more stems
330 are characterized for the same field effort. We estimate that about 40 % of the time used in
331 the distance method was spent on measuring the perpendicular distances – greater efficiency
332 might be achieved if this could be simplified, e.g. using an automatic range finder.

333 The selection of an appropriate sampling method involves consideration of the
334 efficiency of each method under the specific circumstances of the study. Distance methods
335 allow more precise density estimates than the belt-transect method under most conditions.
336 Nonetheless there are differences with location and criteria used (Fig.3). If we simply
337 consider number of transects we see that the biggest differences in confidence by method
338 arises in landscape C (Fig 3a). The use of Distance in landscape C also provides the greatest
339 precision by stem and per man hour (Fig 3b,c) though there is less overall variation by the
340 latter two measures. This reflects the much lower number of observations from the belt-
341 transect method compared to the distance method in landscape C, where visibility is better
342 than in the other two landscapes, allowing higher detection probabilities at a given distance
343 and improved precision and accuracy. The one exception where the belt method
344 outperforms the Distance approach occurs in landscape A where the Distance method is just
345 marginally less precise. This reflects low visibility with few additional trees recorded
346 beyond the belt transects – notably the Distance method still performs better per man-hour
347 even under these conditions. When we consider relative confidence the overall variation
348 seems more marked though the distance methods outperform the belt transects in all cases –
349 the most precise estimates derive from landscape B reflecting the intermediate conditions of
350 the other two landscapes in terms of visibility and in that landscape and a low variation
351 among the transects. The belt transect perform especially poorly in the low density
352 population of landscape C, especially per transect and per man-hour (Fig 3d, f) while the
353 distance approach for this landscape achieves a relative precision comparable to that for the
354 other landscapes.

355

356 **Conclusions**

357 Estimates from the visual detection line-transect method were more reliable than the
358 belt-transect method for a given amount of effort. We recommend that the visual detection
359 line-transect can be effectively used to inventory low abundance but distinctive tree species
360 even in situations with relatively low visibility and considerable variation in size – though
361 further studies on the nature of associated biases and how they may be minimized is
362 justified.

363

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371

372

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Table 1 Comparison of density estimated by the belt-transect method and the selected distance models within the three study landscapes (A, B & C) in Bwindi Impenetrable National Park

<i>Landscape</i>	<i>Tree population</i>	<i>Density estimate</i>		<i>Distance model parameters</i>			<i>---- 95 % CI ----</i>		<i>ESW (m)and *</i>
		<i>Belt (trees/ha)</i>	<i>Distance (trees/ha)</i>	<i>Model/ Series</i>	<i>AIC</i>	<i>GoF (p-value)</i>	<i>Belt estimate</i>	<i>Distance estimate</i>	
A	Seedlings	3.38 ± 0.46	3.91 ± 0.61	H/C	191.4	0.67	2.46 – 4.29	2.92 – 5.20	4.87
A	Saplings	2.00 ± 0.33	3.17 ± 0.40	Hn/C	156.9	0.95	1.36 – 2.64	2.61 – 3.85	5.73
A	Small adults	3.31 ± 0.38	3.32 ± 0.42	Hn/C	293.4	0.56	2.57 – 4.06	2.89 – 3.93	10.15
A	Large adults	6.75 ± 0.52	7.28 ± 0.78	Hn/C	1151	0.68	5.74 – 7.76	6.75 – 7.85	17.21
A	All sizes combined	15.44 ± 0.41	16.34 ± 0.85	Hn/C	1932	0.41	14.91 – 17.94	15.03 – 17.73	13.01
	Summation of sub-populations	<i>15.44</i>	<i>17.68</i>						
B	Seedlings	2.94 ± 0.35	4.83 ± 0.82	H/C	148.7	0.79	2.25 – 3.63	2.90 - 8.10	4.91
B	Saplings	2.06 ± 0.39	2.81 ± 0.41	H/C	158.7	0.4	1.30 – 2.82	2.09 – 3.76	5.69
B	Small adults	1.69 ± 0.36	2.13 ± 0.37	Hn/C	168.4	0.38	0.99 – 2.38	1.81 – 2.51	11.74
B	Large adults	4.44 ± 0.39	4.85 ± 0.46	Hn/C	895.1	0.71	3.68 – 5.20	4.42 – 5.30	19.28
B	All sizes combined	11.13 ± 0.31	11.47 ± 0.94	Hn/C	566.5	0.67	10.51 – 11.74	10.64 - 12.37	12.79
	Summation of sub-populations	<i>11.13</i>	<i>14.87</i>						
C	Seedlings	1.68 ± 0.46	2.23 ± 0.47	Hn/SP	118.3	0.93	1.24 – 2.14	1.88 – 2.63	6.4
C	Saplings	1.00 ± 0.52	1.34 ± 0.45	Hn/C	101.2	0.56	0.49 – 1.51	0.99 – 1.81	6
C	Small adults	0.50 ± 0.25	1.16 ± 0.32	Hn/SP	105.8	0.91	0.01 – 0.99	0.92 – 1.47	11.87
C	Large adults	1.13 ± 0.60	1.22 ± 0.35	U/C	294.3	0.99	0.43 – 1.83	1.06 – 1.45	28.68
C	All sizes combined	4.31 ± 0.84	4.99 ± 0.68	Hn/C	633.3	0.71	2.67 – 5.96	4.47 – 5.57	14.66
	Summation of sub-populations	<i>4.31</i>	<i>5.95</i>						

Density estimate = Mean ± standard error; Hn/P = Half-normal/Simple Polynomial, Hn/C = Half-normal/Cosine, U/C = Uniform/Cosine and H/C = Hazard/Cosine.

AIC = Akaike Information Criterion; GoF = Goodness of fit test probability value; 95 % confidence interval (CI); ESW = Distance effective strip width used; * = Fixed strip width of the belt (5m).

Table 2 Coefficient of variation (% CV), per cent relative bias (PRB) of the visual detection line-transect and the belt-line transect density estimates for different populations of *M.holstii* trees at A, B and C, Bwindi Impenetrable National Park.

Landscape	Tree category	% CV		PRB
		(VDLT method)	(Belt-transect method)	
A	Seedlings	14.51	15.03	-13.55
A	Saplings	9.87	17.84	-36.91
A	Small adults	10.75	12.55	-0.30
A	Large adults	6.55	8.80	-7.28
A	All combined	4.72	5.90	-5.51
B	Seedlings	11.54	13.05	-42.13
B	Saplings	14.67	20.41	-26.69
B	Small adults	9.30	22.93	-20.66
B	Large adults	4.50	8.80	-8.45
B	All combined	3.84	5.08	-1.42
C	Seedlings	13.58	29.43	-24.66
C	Saplings	10.80	55.99	-25.37
C	Small adults	7.38	108.18	-56.90
C	Large adults	7.90	57.57	-7.38
C	All combined	5.57	21.02	-17.27

% CV = $100 \times \{(\text{Standard error}/\text{Density})\}$ and PRB = $100 \times \{(\text{Estimated Density by the belt-transect method} - \text{Estimated density by the distance method}) / \text{Estimated density by the distance method}\}$. Bold figures show population were the visual detection line-transect approaches had better precision. VDLT = Visual detection line-transect method.

Table 3 Comparison of economic efficiencies of belt and distance sampling methods at A, B and C study landscapes in Bwindi Impenetrable National Park.

Study landscape	Efficiency Parameters					
	a) Belt sampling			b) Distance sampling		
	Man – hours/transaction (hr)	Trees within a transect/ man-hrs (No/hr)	Cost of sampling a tree (Shillings/tonne)	Man – hours/transaction (hr)	Trees within a transect/ man-hrs (No/hr)	Cost of sampling a tree (Shillings/tonne)
A	1.23	5.15	340	2.03	14.02	206
B	1.25	3.71	480	2.13	10.65	285
C	1.10	1.44	1088	1.96	5.02	556

Same number of field crews was employed in each of the method and cost of man-hour (Ug.Shs) = 1424.

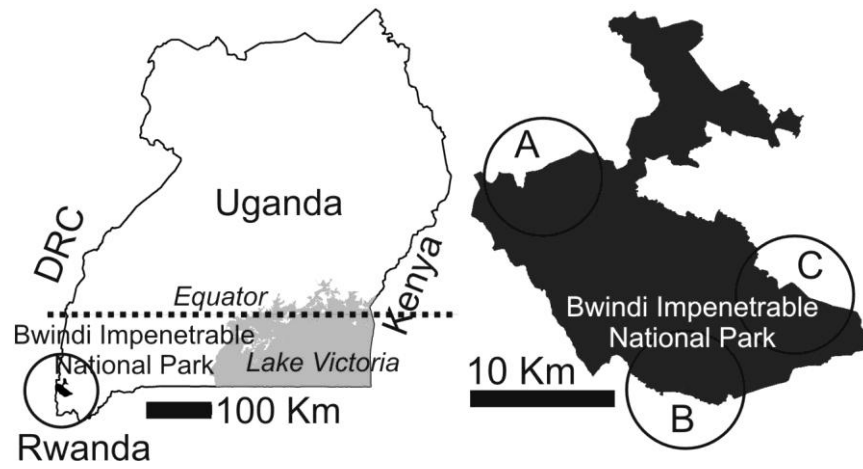


Figure 1 Map showing the study landscapes (A, B, C) and orientation of transects within Bwindi Impenetrable National Park.

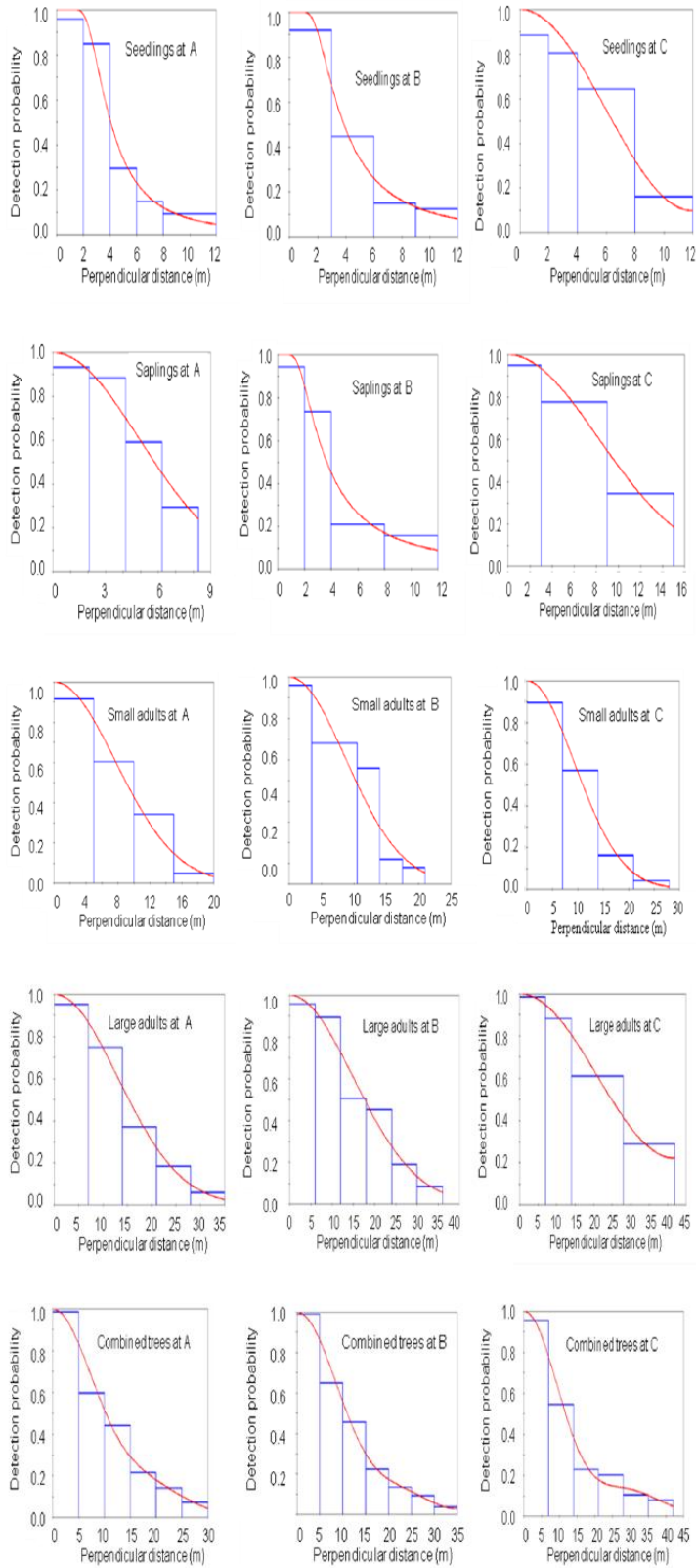


Figure 2 Observed frequency histograms of distance data and the selected best detection functions for different populations of *M. holstii* (Table 1) at A, B and C landscapes in Bwindi Impenetrable National Park.

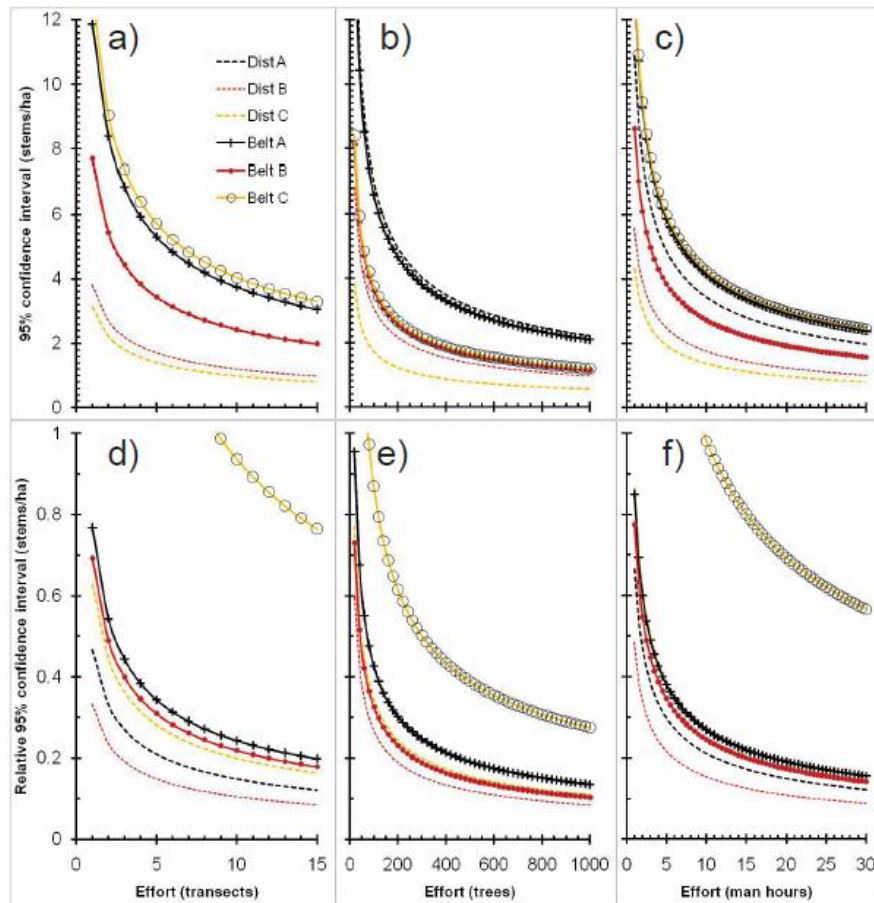


Figure 3 Width of the complete 95% confidence interval (upper to lower) around the estimated stem density (a, b, c,) and relative 95% confidence interval (upper to lower divided by mean, d, e, f) for three landscapes using both distance (Dist) and belt transects (Belt) for three measures of effort: number of transects (a, d), number of stems recorded (b, e) and man hours (c, f). In figure (a) the Dist A and Belt B lines lie nearly on top of each other and in figure (e) Dist A and Belt A and Dist B and Belt C are nearly on top of each other, while in figure (f) Dist A and Belt A are nearly on top of each other.