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Brouwers, N.C. , Newton, A.C., Watts, K. and Bailey, S. (2010) Evaluation of buffer-radius modelling approaches used in forest conservation and planning. *Forestry*, 83 (4). pp. 409-421.

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1 Full reference:

2 **Brouwers, N.C.**, Newton, A.C., Watts, K., Bailey, S., 2010. Evaluation of buffer-radius
3 modelling approaches used in forest conservation and planning. **Forestry** 83, 409-421.

4

5 Title:

6 **Evaluation of buffer-radius modeling approaches used in forest conservation**
7 **and planning**

8

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10

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37

38 **Summary**

39

40 Spatial modeling approaches are increasingly being used to direct forest management
41 and conservation planning at the landscape scale. A popular approach is the use of
42 buffer-radius methods, which create buffers around distinct forest habitat patches to
43 assess habitat connectivity within anthropogenic landscapes. However, the
44 effectiveness and sensitivity of such methods has rarely been evaluated. In this study,
45 Euclidean and least-cost buffer-radius approaches were used to predict functional
46 ecological networks within the wooded landscape of the Isle of Wight (UK). To
47 parameterize the models, a combination of empirical evidence and expert knowledge
48 was used relating to the dispersal ability of a model species, the wood cricket
49 (*Nemobius sylvestris* Bosc.). Three scenarios were developed to assess the influence
50 of increasing the amount of spatial and species specific input data on the model
51 outcomes. This revealed that the level of habitat fragmentation for the model species is
52 likely to be underestimated when few empirical data are available. Furthermore, the
53 least-cost buffer approach outperformed simple Euclidean buffer in predicting presence
54 and absence for the model species. Sensitivity analyses on model performance
55 revealed high sensitivity of the models to variation in buffer distance (i.e. maximum
56 dispersal distance) and permeability of common landscape features such as roads,
57 watercourses, grassland, and semi-natural habitat. This indicates that when data are
58 lacking with which to parameterize buffer-radius models, the model outcomes need to
59 be interpreted with caution. This study also showed that if sufficient empirical data are
60 available, least-cost buffer approaches have the potential to be a valuable tool to assist
61 forest managers in making informed decisions. However, least-cost approaches should
62 always be used as an indicative rather than prescriptive management tool to support
63 forest landscape conservation and planning.

64

65 Keywords: forest habitat networks; buffer-radius models; sensitivity analyses; forest
66 landscape conservation; insect; invertebrate
67
68

69 Introduction

70

71 In many parts of the world, forested landscapes have undergone substantial changes
72 as a result of anthropogenic activities such as agriculture and urban development (Dale
73 *et al.*, 2000; Forman, 1995; Jongman and Pungetti, 2004; Lindenmayer and Fischer,
74 2006; Newton *et al.*, 2009a). This has resulted in an overall loss of forest cover and
75 increased fragmentation of forest habitats within the landscape (e.g. Newton, 2007;
76 Reed *et al.*, 1996; Saunders *et al.*, 1991). Forest habitat loss and fragmentation are
77 widely recognized as principal causes of declines in biodiversity at many different
78 geographical locations (Andrén, 1994; Driscoll and Weir, 2005; Fahrig, 2003; Niemelä
79 *et al.*, 2007).

80

81 Many landscapes are now dominated by agricultural land with remnants of natural and
82 semi-natural habitat embedded within them. In addition to the direct effects of area loss
83 and isolation (MacArthur and Wilson, 1967), the degree of connectivity between such
84 habitat fragments has a major influence on species persistence within these
85 landscapes (Bennett, 2003; Crooks and Sanjayan, 2006; Hanski and Gilpin, 1997).

86 [Habitat connectivity, in terms of the ability of a species to move between distinct habitat
87 patches in a landscape, is highly species-specific \(Lindenmayer and Fischer, 2006;](#)

88 [Taylor *et al.*, 2006\)](#), and the degree of isolation between fragments is primarily

89 influenced by the physical ability of individual species to disperse (Turchin, 1998).

90 Furthermore, it is increasingly recognized that the characteristics of the matrix (*i.e. non-*

91 [natural habitat like arable land](#)) surrounding habitat fragments may have a strong

92 influence on the degree of habitat connectivity and the responses of species to

93 isolation (Lindenmayer and Fischer, 2006; Lindenmayer and Franklin, 2002; Taylor *et*

94 *al.*, 2006). The resistance or permeability of the matrix may increase ecological

95 isolation by reducing the probability of species movement between habitat patches,
96 thereby influencing the species' sensitivity to fragmentation.

97

98 Creation of habitat networks provides a potential approach to combat the deleterious
99 effects of habitat loss and fragmentation and has been implemented worldwide across
100 a range of scales (Bailey, 2007; Bennett, 2003; Jones-Walters, 2007; Jongman and
101 Pungetti, 2004; Peterken, 2000; Peterken, 2002; Quine and Watts, 2009). For example,
102 in the UK financial support has been provided by the Government to develop a
103 program aimed at rejoining ancient woodland sites (Quine and Watts, 2009), towards
104 creating forest habitat networks. The approach of creating habitat networks is based on
105 the principle that increasing connectivity between habitat fragments within a landscape
106 will facilitate movements and dispersal of organisms (Boitani *et al.*, 2007; Lindenmayer
107 and Fischer, 2006). This is thought to benefit the persistence and survival of species,
108 for example by facilitating genetic exchange and supporting the dynamics of
109 metapopulations (Crooks and Sanjayan, 2006; Driezen *et al.*, 2007; Hanski and Gilpin,
110 1997). Across Europe the importance of the creation of habitat networks to maintain
111 and enhance biodiversity is now generally recognized in cross-sectoral policy initiatives
112 (Jones-Walters, 2007), [although validation of this approach is still limited \(Bailey, 2007;](#)
113 [Boitani *et al.*, 2007\).](#)

114

115 In order to aid the planning and development of forest habitat networks, a number of
116 modeling approaches and tools have been developed. [These tools are used to](#)
117 [evaluate the degree of habitat connectivity, not only from a landscape/structural \(i.e.](#)
118 [human\) perspective \(e.g. Quine and Watts, 2009\), but increasingly from a more](#)
119 [functional \(i.e. species-centred\) point of view, accounting for matrix permeability](#)
120 [\(Crooks and Sanjayan, 2006; Driezen *et al.*, 2007\).](#) Such spatial modeling approaches
121 are increasingly being used to inform the development of forest management and
122 conservation plans at the landscape scale (Bailey, 2007; Calabrese and Fagan, 2004;

123 Fagan and Calabrese, 2006; Gillespie *et al.*, 2009; Humphrey *et al.*, 2009; Humphrey
124 *et al.*, 2005; Moilanen and Nieminen, 2002; Watts *et al.*, 2007). Other approaches that
125 account for species-specific habitat connectivity include LARCH, which utilizes
126 individual-based movement models (Opdam *et al.*, 2006; van Rooij *et al.*, 2003) and
127 Conefor Sensinode (Pascual-Hortal and Saura, 2006; Saura and Pascual-Hortal, 2007),
128 which adopts a graph theory approach to connectivity.

129

130 A popular group of spatial models used to examine functional habitat connectivity
131 within fragmented landscapes are buffer-radius models (Fagan and Calabrese, 2006).
132 These combine spatial data describing landscape structure with species-specific data
133 on dispersal (Calabrese and Fagan, 2004; Fagan and Calabrese, 2006; Moilanen and
134 Nieminen, 2002). A number of alternative buffer-radius approaches have been
135 developed (Calabrese and Fagan, 2004) that incorporate Euclidean distances and
136 functional distances, utilizing least-cost distance approaches (Adriaensen *et al.* 2003)
137 to account for matrix permeability. Within the UK, the Forest Research Agency of the
138 Forestry Commission has been developing and utilizing least-cost buffer-radius
139 modeling approaches under the banner of Biological and Environmental Evaluation
140 Tools for Landscape Ecology (BEETLE) (Watts *et al.*, 2005). This approach has been
141 used to identify potential networks (Catchpole, 2007; Catchpole, 2006) and to assist
142 forest and landscape managers to maintain and develop sustainable forest landscapes
143 (Watts *et al.*, 2008; Watts *et al.*, 2007).

144

145 Buffer-radius modeling approaches have been found to be sensitive to the buffer
146 distance (Moilanen and Nieminen, 2002) and, in particular, to the permeability
147 parameters used in least-cost approaches (Moilanen and Nieminen, 2002). This
148 indicates that if specific species are targeted for habitat network analysis, the dispersal
149 and permeability parameters need to be accurate in order to make sound predictions.
150 However, these estimates are generally unavailable and/or difficult to obtain because

151 of the amount of resources and time required to collect the species-specific information
152 needed (Fagan and Calabrese, 2006). As a result, these parameters are often based
153 on expert opinion alone (Beier *et al.*, 2009). Furthermore, the output of buffer-radius
154 approaches are rarely tested for their accuracy in predicting functional habitat networks
155 within real landscapes (Driezen *et al.*, 2007), and sensitivity analyses of these
156 approaches have rarely been undertaken (Gillespie *et al.*, 2009; Humphrey *et al.*, 2009).
157 However, testing the robustness of connectivity models is essential to evaluate the
158 value and accuracy of the model outcomes (Beier *et al.*, 2009; Beier *et al.*, 2008). As a
159 consequence, the validity of simple buffer-radius models in conservation planning has
160 been questioned (e.g. Calabrese and Fagan, 2004; e.g. Fagan and Calabrese, 2006;
161 Moilanen and Nieminen, 2002), as their simplicity was found not to be adequate
162 compensation for a lack of accuracy (Moilanen and Nieminen, 2002). Incorporating
163 more species-specific dispersal information within buffer-radius models could
164 potentially improve their performance and increase their value for supporting decision-
165 making (Calabrese and Fagan, 2004). There is therefore a need to evaluate different
166 buffer-radius approaches informed by actual species data, with respect to their level of
167 accuracy for predicting functional habitat networks within real landscapes.

168

169 This paper provides a comparative analysis of buffer-radius modeling approaches used
170 in forest conservation management to identify forest habitat networks in a fragmented
171 landscape. This study used empirical data for a model species, wood cricket
172 (*Nemobius sylvestris*), which has been the subject of detailed field-based research.
173 Previous empirical studies on this insect has focused on its (i) distribution and
174 occurrence at the landscape scale, (ii) habitat requirements, and (iii) dispersal ability
175 through different habitat and landscape features (Brouwers and Newton, 2009a;
176 Brouwers and Newton, 2009b; Brouwers and Newton, in press; Brouwers *et al.*, 2009).
177 This research indicated that wood cricket is an 'edge specialist', generally found on the
178 margins of forest fragments, and displaying limited movements into surrounding

179 landscape features (i.e. it is matrix-sensitive). In comparison with other forest related
180 insects, the species is considered to be a poor to moderate disperser (Brouwers and
181 Newton, 2009c; Brouwers and Newton, in press), able to disperse up to 60 m through
182 forest habitat during the entire life cycle (Morvan *et al.*, 1978). Movement through non-
183 forest vegetation, such as grasslands, was found to be restricted. Wood cricket was
184 able to cross small watercourses, but generally avoided crossing linear landscape
185 features such as roads, which therefore represent possible dispersal barriers (Morvan
186 and Campan, 1976` ; Brouwers, personal observation). These empirical data combined
187 with field observations of the species were used to parameterize and build alternative
188 buffer-radius network models and to compare the model outcomes.

189

190 This study aims to address the following objectives: (1) to investigate the influence of
191 data availability on the model outcomes; (2) to compare the alternative network models,
192 informed by empirical data, in predicting patch occupancy for wood cricket on the Isle
193 of Wight (UK); and (3) to conduct a sensitivity analysis of the various parameters used
194 in the network models.

195

196 **Materials and methods**

197

198 *Study area*

199

200 The Isle of Wight (UK) was used as the basis for this study as it represents a highly
201 fragmented landscape, typical for much of lowland England, with forest fragments
202 situated within a predominantly agricultural matrix. The total surface area of the Isle of
203 Wight is approximately 380 km², with forest covering approximately 50 km² or 13% of
204 the island area. Of the total forest area, 32% is classified as forest still retaining ancient
205 characteristics, of which 17% is classified as ancient semi-natural woodland (i.e. pre-

206 1600 AD native broadleaf woodland) and the remaining 15% are planted ancient
207 woodland sites (i.e. pre-1600 AD woodland that was converted/planted with non-native,
208 mainly coniferous, tree species). The remaining forest areas are of more recent origin
209 (i.e. post-1600 AD native woodlands) and/or are plantations (Smith and Gilbert, 2003).
210 On the Isle of Wight, several forest restoration schemes have been carried out,
211 including targeted landscape-scale habitat creation schemes aiming to enlarge and join
212 ancient woodlands (Quine and Watts, 2009).

213

214 *Survey data*

215

216 In 2005, a landscape-scale survey was undertaken on wood cricket targeting individual
217 forest fragments on the Isle of Wight. A total of 147 individual fragments were surveyed
218 of which 32 were occupied by wood cricket populations while the remaining 115
219 fragments were unoccupied at that particular time (Brouwers and Newton, 2009b).
220 Fragment boundaries were defined either by neighboring agricultural land (grassland or
221 arable) or by distinct anthropogenic/natural landscape features (urban fringes, tarmac
222 roads, railway lines, rivers and watercourses) (Brouwers and Newton, 2009b). These
223 data combined with field data gathered in 2006 and 2007 on the habitat preferences
224 (Brouwers and Newton, 2009a) and dispersal ability of wood cricket (Brouwers and
225 Newton, 2010; Brouwers and Newton, in press; Brouwers *et al.*, unpublished data),
226 were used to run and evaluate the alternative buffer-radius modeling approaches.

227

228 *Modeling*

229

230 In this study, three scenarios were developed to generate potential habitat networks for
231 wood cricket on the Isle of Wight using a Euclidean and a least-cost buffer-radius
232 approach. These three scenarios utilized increasing amounts of empirical data, in order

233 to investigate the influence of data availability on the model outcomes. The first
234 scenario required the least amount of input data and used a simple Euclidean distance
235 buffer approach, based on recorded maximum dispersal distance (Scenario 1). This
236 approach creates an equidistant buffer around each forest fragment following the
237 contours of its boundary. The areas that overlap are merged, each representing a
238 potential habitat network where movement of the target species is believed to occur.
239 The other two scenarios that were developed utilized least-cost distance approaches,
240 which require, besides the maximum dispersal distance, additional data on the
241 dispersal ability of the species through the different landscape features. This approach
242 uses a buffer based on the maximum dispersal distance, weighted by the underlying
243 permeability of the surrounding land cover. In this case, permeable land cover features
244 will extend or stretch the buffer, whereas more hostile landscape features will contract
245 or reduce the buffer extent. As with the previous method, areas that overlap are
246 merged and treated as potential habitat networks. Scenario 2 and 3 differed by the
247 detail of the surrounding land cover utilized, as detailed below.

248

249 The network analysis was conducted by a custom-made least-cost network extension
250 within ArcGIS, developed by Forest Research (FR) under the banner of BEETLE
251 (Watts *et al.*, 2005). This tool maps the potential network for a species within a
252 landscape based on its maximum dispersal distance, and the predicted ability of a
253 species to move through different landscape features (Watts *et al.*, 2005).

254

255 Four digitized land cover maps were used to generate the habitat networks for the
256 three different scenarios. 'Map 1' represented all forest habitats on the Isle of Wight,
257 and was derived from the National Inventory of Woodland and Trees (NIWT) (Smith
258 and Gilbert, 2003). 'Map 2' was compiled using data included in Map 1 and Ordnance
259 Survey digital data (OS MasterMap, Ordnance Survey, Southampton, United Kingdom),
260 excluding roads, inland water bodies, and watercourses intersecting the forest habitat.

261 'Map 3' combined the forests included in Map 1 with Land Cover Map 2000 (LCM2000,
262 CEH, Wallingford, UK) digital data for the Isle of Wight. The LCM2000 dataset defines
263 all the different land cover types on the Isle of Wight based on a computer classification
264 of satellite scenes, obtained mainly from Landsat satellites with a resolution of 25x25 m
265 (CEH Monks Wood, Huntingdon, England). 'Map 3' therefore represented all forest
266 habitats and all other land cover features represented in the LCM2000 dataset,
267 including semi-natural landscape features, grassland, arable, estuaries and urban
268 developed land. 'Map 4' combined the edited forests included in Map 2 with Land
269 Cover Map 2000 (LCM2000, CEH, Wallingford, UK), and the OS MasterMap data for
270 roads, small inland water bodies and watercourses respectively. 'Map 4' therefore
271 included all landscape features represented in Map 3, but also included the separate
272 features for roads, inland water bodies and watercourses. All maps were compiled
273 using general editing features available in ArcGIS (9.1) (Table 1).

274

275 *#Table 1 Approx here#*

276

277 Based on the maximum dispersal distance observed for wood crickets (Morvan *et al.*,
278 1978; Brouwers, personal observation), for all three scenarios a buffer distance (i.e.
279 maximum dispersal distance) of 60 m was used (Table 2). For Scenario 1, an
280 equidistant buffer was created around the forest fragments included in 'Map 1'. For
281 Scenarios 2 and 3, the permeability of each feature was calculated by dividing the
282 buffer distance by the assigned cost value (see Table 2). These cost values were
283 based on empirical data and field observations of wood cricket gathered over the
284 course of three years of intensive study (Brouwers and Newton, 2009a; Brouwers and
285 Newton, 2009b; Brouwers and Newton, in press; Brouwers *et al.*, 2009). Scenario 2
286 calculated forest habitat networks within the landscape without the influence of roads,
287 inland water bodies and watercourses combining 'Map 1' and 'Map 3' (Table 1).
288 Scenario 3 included the influence of roads, inland water bodies and watercourses

289 combining 'Map 2' and 'Map 4' to generate the potential forest habitat networks (Table
290 1). Additionally, the model built in Scenario 3 included all the combined knowledge on
291 the dispersal ability of the study species, and can therefore be considered as the most
292 informed model in terms of predicting functional forest habitat networks for wood cricket.
293 For each scenario, after the buffers were created around each forest fragment, all
294 forests overlapping or touching each other were defined as an individual network. All
295 predicted habitat networks that were created with these scenarios therefore contained
296 one or more distinct forest fragments that are currently present within the landscape of
297 the Isle of Wight.

298

299 *#Table 2 Approx here#*

300

301 *Model comparison*

302

303 Differences between the model-scenarios were based on variation of data used to run
304 and build the models. The amount of data that was used increased with each
305 successive model scenario (i.e. Scenarios 1 – 3 respectively). To investigate the
306 influence of data availability using the three model scenarios (objective 1), the
307 differences between the model outcomes were evaluated with the following
308 comparative analyses.

309

310 *Analysis one*

311

312 To test for differences in the total number of networks that were generated for all the
313 forest fragments on the Isle of Wight, chi-square 'goodness of fit' tests were performed.
314 Between each scenario, the total number of networks that was generated was tested
315 against expected values of equal size.

316

317 *Analysis two*

318

319 To test if the surface area of the networks that were generated differed between the
320 scenarios, individual Mann-Whitney *U* tests were performed to test for differences in
321 the median network size between each scenario.

322

323 *Analysis three*

324

325 To reveal if differences in the scenarios were shown for networks with known
326 presence/absence for wood crickets, differences between the outcomes of the
327 scenarios were further tested using a sub-sample of the forest fragments that were
328 surveyed in 2005 ($n = 147$). For these tests, the networks that included a surveyed
329 forest were included in the analyses. Differences in the number of surveyed networks
330 between the scenarios were tested against expected values of equal size using chi-
331 square 'goodness of fit' tests.

332

333 *Analysis four*

334

335 To compare the alternative scenarios in predicting patch occupancy for wood cricket on
336 the Isle of Wight (UK) (objective 2), only networks including occupied forests were
337 considered. In this case, the number of unoccupied forests included in the occupied
338 networks was compared and tested against expected values of equal size using chi-
339 square 'goodness of fit' tests.

340

341 *Analysis five*

342

343 For each scenario, the network area of occupied and unoccupied networks was
344 compared using Mann-Whitney *U* tests. This test was performed to confirm earlier

345 findings on the positive effect of patch and network size on species and wood cricket
346 presence (Brouwers and Newton, 2009b; MacArthur and Wilson, 1967).

347

348 *Sensitivity analyses*

349

350 To test how sensitive the models were to variations in the input variables, a series of
351 sensitivity analyses were conducted (objective 3).

352

353 *Analysis six*

354

355 First, to compare the influence of the buffer distance (i.e. dispersal distance),
356 simulations applying distances in the range of 5 - 500 m were used to generate
357 networks for the three different scenarios. The differences between the scenarios were
358 compared by plotting the number of networks that were generated against buffer
359 distance.

360

361 *Analysis seven*

362

363 Scenario 3 incorporates the highest amount of empirical data related to the dispersal
364 ability of the study species (see Methods, Modeling), and can therefore be considered
365 likely to be the most accurate in terms of predicting functional forest habitat networks.
366 Where a certain amount of expert knowledge was used to assign the cost values to the
367 different landscape features that were incorporated in the maps to generate the
368 networks, a further series of sensitivity analyses was conducted for Scenario 3. For
369 these analyses, the cost values that were primarily based on field observations were
370 varied for the four main groups of non-forest habitat (see Table 2 and Table 3). For all
371 of these series, the total number of networks generated was compared with the original
372 number generated under Scenario 3 and tested against expected values of equal size

373 using chi-square 'goodness of fit' tests. All statistical tests mentioned in the analyses
374 were performed using SPSS 14.0 for Windows (SPSS Inc., Chicago, Illinois, USA).

375

376 *#Table 3 Approx here#*

377

378 **Results**

379

380 *Model comparison*

381

382 *#Figure 1a-c Approx here#*

383

384 *#Figure 2a-c Approx here#*

385

386 Based on the variation of input data used to run and build the model scenarios, the
387 following differences were found when comparing the model outcomes (objective 1). A
388 larger number of networks was generated with consecutive Scenarios (1 – 3) (Figure 1,
389 2). Where the Euclidean buffer-radius approach (Scenario 1) generated one network,
390 the least cost buffer-radius Scenarios 2 and 3 generated 5 and 10 networks for the
391 same area respectively (see Figure 2), indicating an increased degree of forest
392 fragmentation.

393

394 *#Figure 3a-c Approx here#*

395

396 *#Table 4 Approx here#*

397

398 Analysis one revealed that for each successive scenario a higher number of networks
399 was generated (Table 4), indicating a higher level of predicted fragmentation of forest

400 habitat between consecutive scenarios (i.e. with increasing detail of digital data and
401 knowledge of the dispersal ability of the model species used). Furthermore, analysis
402 two revealed that the total network area decreased with each consecutive scenario
403 (see caption Figure 3), indicating a decreasing amount of habitat availability within
404 individual habitat networks between consecutive scenarios. Further results of the
405 analyses comparing the model outputs of the three different scenarios are presented in
406 Table 4. When considering the sub-sample of networks including a surveyed forest,
407 analysis three showed that each successive scenario generated a higher total number
408 of networks (Table 4). For all unoccupied and occupied networks, each successive
409 scenario also generated a higher total number (Table 4). Together these results
410 indicated that the amount of detailed species data that was used in the model
411 scenarios had a significant influence on the outcome of the simulations.

412

413 To compare the alternative network models further, tests were performed to examine
414 their ability to predict patch occupancy for wood cricket on the Isle of Wight (UK)
415 (objective 2). When specifically considering the sub-sample of occupied networks,
416 analysis four revealed that the number of surveyed unoccupied forests decreased with
417 each successive scenario (with $n = 32$ for surveyed occupied forests) (Table 4). The
418 number of surveyed unoccupied forests included in the occupied networks was found
419 to be significantly higher in Scenarios 1 compared to Scenarios 2 and 3, but there was
420 no difference between Scenarios 2 and 3 (Table 4). Furthermore, percentage of patch
421 occupancy within the predicted occupied networks increased with the successive
422 scenarios used (Table 4). This indicates that for the model species, the least-cost
423 buffer approach outperforms the Euclidean buffer approach in predicting patch
424 occupancy within fragmented landscapes.

425

426 Additionally, analysis five showed that for each scenario, occupied networks were
427 found to be larger than unoccupied networks (Mann-Whitney U test: Scenario 1,

428 median occupied = 125.07 ha, median unoccupied = 14.81 ha, $U = 78.000$, $z = -3.094$,
429 $P = 0.002$; Scenario 2, median occupied = 51.45 ha, median unoccupied = 7.05 ha, $U =$
430 189.000 , $z = -3.523$, $P < 0.001$; Scenario 3, median occupied = 25.60 ha, median
431 unoccupied = 8.16 ha, $U = 479.000$, $z = -2.411$, $P = 0.016$), confirming previous
432 findings (Brouwers and Newton, 2009b). This indicates that wood crickets are most
433 likely to be found in areas within the landscape where forest cover is high (see
434 relatively large networks, Figure 1).

435

436 Altogether, these analyses indicate a significant improvement in the performance of
437 buffer-radius models when more detailed information on the dispersal ability of the
438 model species and supporting data on environmental data are used.

439

440 *Sensitivity analyses*

441

442 *#Figure 4 Approx here#*

443

444 To address objective 3, a series of sensitivity analyses of the various parameters used
445 in the network models was performed. Analysis six revealed that the number of
446 networks generated by Scenarios 1 – 3 decreased with increasing buffer distance
447 (Figure 4). Overall, the Euclidean buffer approach (Scenario 1) showed the highest
448 sensitivity for changes in the buffer distance used. The number of individual networks
449 showed a rapid exponential decrease with increasing buffer distance (Figure 4).

450 Compared to the least-cost buffer approach (Scenarios 2 and 3), this indicates that
451 small inaccuracies in estimating dispersal distances for a species can result in a
452 significant underestimation of the number of functional networks and an overestimation
453 of the level of connectivity for forest habitat when using a Euclidean buffer approach.

454 When including more detail in the digital data for the least-cost approach (Scenarios 2

455 and 3), by including linear features (i.e. roads and watercourses) in Scenario 3, the
456 sensitivity for buffer distance was higher compared to Scenario 2 at low values but
457 comparable at higher values (Figure 4). This indicates that when including more detail,
458 such as small linear features functioning as dispersal barriers, the accuracy of the
459 estimated dispersal distance becomes increasingly important to model outcomes.

460

461 *#Table 5 Approx here#*

462

463 To test the sensitivity of the most detailed and realistic model scenario (Scenario 3)
464 that was used in this study, the influence of the permeability of the three main groups of
465 non-forest landscape features were tested by varying the cost values for these groups
466 (see Methods, Analysis seven). In sensitivity Series 1, decreasing the permeability of
467 estuaries, roads and inland water bodies and watercourses from 1 m (cost 60) to 0.1 m
468 (cost 600) did not change the total number of networks that was generated ($n = 532$,
469 Table 5). Increasing the permeability of these features from 1 m to 1.5 m (cost 40)
470 significantly decreased the number of networks (Table 5). [These results indicate a high
471 sensitivity of the least-cost method when slightly decreasing the cost value \(i.e. slightly
472 increasing the permeability\) of narrow linear landscape features.](#) Furthermore,
473 excluding minor roads as landscape features within the analysis revealed that
474 significantly fewer networks were generated than when minor roads were included (chi-
475 square: $n_{\text{incl minor}} = 532$, $n_{\text{excl minor}} = 457$, $\chi^2 = 5.688$, $df = 1$, $P = 0.017$, Table 5). This
476 indicates that including the influence of minor roads had a large effect on the outcome
477 of Scenario 3. For sensitivity Series 2, increasing the permeability of the semi-natural
478 landscape features and grassland from 30 m (cost 2) to 60 m (cost 1) decreased the
479 number of networks significantly (Table 5). Decreasing the permeability of these
480 features from 30 m (cost 2) to 10 m (cost 6) did not significantly increase the number of
481 networks (Table 5). Both results indicate a moderate effect of these features on the
482 outcome of Scenario 3. For sensitivity Series 3, increasing the permeability of arable

483 and urban developed land from 10 m (cost 6) to 30 m (cost 2) did not significantly
484 decrease the number of networks generated (Table 5). This indicates a minor effect of
485 these features on the outcome of Scenario 3.

486

487 Together these sensitivity analyses indicate that the empirical data that are used for
488 simulations with buffer-radius approaches need to be accurate to prevent significant
489 over- or underestimations of the predicted level of connectivity/fragmentation in
490 forested landscapes.

491

492 **Discussion**

493

494 The study presented here demonstrated that the amount of input data used had a
495 major influence on the degree of accuracy that was achieved in predicting functional
496 habitat networks within forested landscapes. Accurate parameterization of buffer-radius
497 models can be very demanding in terms of the amount of resources and time required
498 to collect the species-specific information that is needed (Fagan and Calabrese, 2006).
499 Typically there is a lack of detailed information available on species-specific dispersal,
500 and for this reason, simple buffer-radius approaches are often favored over more data
501 intensive models (Calabrese and Fagan, 2004; Fagan and Calabrese, 2006). This
502 often results in simple measures and modeling approaches being used to make
503 'informed' decisions in landscape conservation management and planning (Calabrese
504 and Fagan, 2004). Simplicity should, however, not be favored over accuracy (Moilanen
505 and Nieminen, 2002), as inaccurate model predictions could have major implications
506 for planning and decision making. Our study showed that the amount and accuracy of
507 input data significantly influenced the outcomes of buffer-radius modeling approaches,
508 and that least-cost buffer outperformed the simple Euclidean buffer approach in
509 predicting functional forest habitat networks for the model species in the forested

510 landscape on the Isle of Wight. Our study further highlights the risk of underestimating
511 the level of forest fragmentation when the simplicity of the buffer-radius approach is
512 favored over accuracy. This indicates that the choice of the buffer-radius model and the
513 amount of input data used will have considerable implications for the level of accuracy
514 that is achieved when making decisions in terms of forest habitat management.

515

516 Forest habitat within landscapes is often fragmented, and forest fragments are often
517 separated from each other by different landscape features (e.g. Quine and Watts,
518 2009). The surrounding matrix has been found to have a considerable impact on the
519 dispersal of species when moving between habitat fragments (Forman, 1995; Turner *et al.*,
520 2001). This was also found for the model species used in this study. The Euclidean
521 buffer-radius approach (Scenario 1) ignores the surrounding matrix habitat completely
522 when simulating habitat networks for species. However, the least-cost approach does
523 incorporate the species response to the matrix (Watts *et al.*, 2005). Intuitively, the
524 Euclidean approach can therefore be considered as a poorer predictor of functional
525 habitat networks than the least-cost buffer-radius modeling approach that was used
526 here (Scenario 2 and 3). Our study showed that least-cost buffer outperformed simple
527 Euclidean buffer in predicting presence and absence for the model species, indicating
528 the higher level of predictive power of least-cost buffer-radius approaches. This
529 supports earlier indications of poorer performance of simple connectivity measures
530 compared to more complex measures that found least-cost distance to be a better
531 predictor for patch occupancy than Euclidean distance (Chardon *et al.*, 2003; Moilanen
532 and Nieminen, 2002). This emphasizes the importance of incorporating the matrix
533 habitat in connectivity models, [achieving a higher level of predictive accuracy. Adopting](#)
534 [least-cost modeling approaches should therefore become the new standard to assist in](#)
535 [landscape conservation and planning.](#)

536

537 Some evidence is available that landscape or structural connectivity increases when
538 forested areas are specifically targeted in conservation initiatives that focus on
539 increasing the degree of habitat connectivity (Quine and Watts, 2009). However,
540 landscape/structural connectivity is measured from a human perspective (Lindenmayer
541 and Fischer, 2006) and does not measure the actual or functional habitat connectivity
542 for species living in the landscape (Crooks and Sanjayan, 2006; Fagan and Calabrese,
543 2006). Furthermore, whether targeted conservation initiatives, like creating habitat
544 networks, are benefiting species living in forest habitat remains largely untested (Bailey,
545 2007; Boitani *et al.*, 2007). The difficulties of measuring the effectiveness of such
546 initiatives for specialized forest-dwelling species mainly lies in the fact that newly
547 created habitat corridors that connect existing habitat fragments need time to develop,
548 before they offer functional connectivity. In the case of forest habitat, meeting the
549 specific habitat requirements of specialized species can take several decades of forest
550 development (Beier *et al.*, 2008). In the UK, forests continue to be the focus of ongoing
551 conservation management involving habitat restoration and expansion (Forestry
552 Commission, 2006). The structural connectivity between habitat networks for forest
553 invertebrates similar to wood crickets was found to have increased during a recent
554 targeted forest restoration scheme on the Isle of Wight (Brouwers *et al.*, 2009; Quine
555 and Watts, 2009). For wood cricket itself, the restoration scheme was successful in
556 increasing structural connectivity in 3 out of 4 areas where wood cricket was known to
557 be present (Brouwers *et al.*, 2009). However, long-term monitoring of species
558 migration and dispersal will be key to evaluate the actual effectiveness of these
559 schemes in terms of increasing functional habitat connectivity for forest species.
560
561 Sensitivity analyses of forest modeling approaches are needed to determine how
562 useful such approaches are for stakeholders involved in conservation management
563 and planning, particularly when available input data is mainly based on expert opinion,
564 as is often the case (Beier *et al.*, 2009; Beier *et al.*, 2008; He, 2008; He *et al.*, 2008;

565 Humphrey *et al.*, 2009). In this study using buffer-radius models, all scenarios and both
566 approaches were found to be highly sensitive to the buffer-distance that was used. This
567 buffer distance was directly related to the maximum dispersal distance observed for the
568 target species of interest. However, for most species accurate estimates for maximum
569 dispersal distance are lacking and are difficult to obtain (Ranius, 2006; Turchin, 1998).
570 These are therefore often necessarily estimated using expert opinion instead of
571 empirical evidence (e.g. Humphrey *et al.*, 2009). However, if dispersal estimates are
572 inaccurate, this can have considerable consequences for the model predictions of
573 buffer-radius approaches, as shown in this study. Additionally, Humphrey *et al.* (2009)
574 specifically highlight the need for sensitivity analyses of the cost values used for the
575 matrix features surrounding forest habitat fragments in least-cost buffer-radius
576 modeling approaches. A sensitivity study on a least-cost model used for corridor design
577 revealed that the model predictions informed by expert opinion were generally robust to
578 variations in the cost values used (Beier *et al.*, 2009). However, our study showed that
579 small variations in the cost values and exclusion of certain anthropogenic features such
580 as small roads had a significant impact on the number of functional forest networks that
581 were predicted. The study of Beier *et al.* (2009) examined seven relatively mobile
582 mammal species and one bird species, whereas our study considered a relatively
583 immobile (i.e. small flightless) invertebrate species, which may explain the difference in
584 results obtained. Additionally, variation in the accuracy of the digitized remote sensed
585 land cover data sets that were used could also have been influential (Driezen *et al.*,
586 2007; Gillespie *et al.*, 2009; Newton *et al.*, 2009b). Such an effect was shown in a case
587 study measuring habitat connectivity using three different remote-sensed datasets for
588 woodland (Gillespie *et al.*, 2009), which found considerable differences between the
589 model outcomes. Our sensitivity analyses indicate that inaccuracies in the input data
590 can have a considerable impact on the predictions of buffer-radius models. This
591 highlights the fact that output maps generated with buffer-radius models should be

592 interpreted with caution, particularly when input values are used based on expert
593 knowledge alone.

594

595 It is increasingly being recognized that conservation initiatives should adopt a
596 community- or ecosystem-based approach rather than examine single target species
597 (e.g. Beier *et al.*, 2008; Fagan and Calabrese, 2006; Vos *et al.*, 2001). Some of the
598 approaches that have been explored in this context are the use of umbrella species
599 (Beier *et al.*, 2009; Fagan and Calabrese, 2006) or the focal species approach (Beier *et*
600 *al.*, 2009; Beier *et al.*, 2008; Eycott *et al.*, 2007; Humphrey *et al.*, 2009). These
601 approaches are aimed at encapsulating the characteristics of a broad range of species
602 linked with a certain habitat. The dispersal values used are assumed to be
603 representative for a range of species (Eycott *et al.*, 2007), [however the validity of this](#)
604 [approach remains largely untested](#). In this study, dispersal characteristics of wood
605 crickets were used to perform the modeling simulations. Wood crickets were found to
606 display similar dispersal rates to a range of other relatively specialized forest species,
607 representing a large group of flightless ground-dwelling insects that spend most of their
608 life cycle in forest habitat (e.g. carabid beetles) (Brouwers and Newton, 2009c;
609 Brouwers and Newton, in press). This suggests that the most informed and realistic
610 model (Scenario 3) that was developed in this study can be used as a tool for
611 predicting functional forest habitat networks within the landscape and used for
612 guidance in directing conservation initiatives for this type of species.

613

614 Based on empirical evidence and expert knowledge of the model species, the most
615 realistic scenario used in this study was the least-cost buffer-radius model including the
616 influence of roads and watercourses (Scenario 3). With this scenario, patch-occupancy
617 of the species within occupied networks was accurately predicted for 57% of the forest
618 fragments that were included. In a metapopulation study, using ecological scaled
619 landscape indices within a metapopulation model, Vos *et al.* (2001) found that patch

620 occupancy was a good indicator of metapopulation viability. Using empirical data for a
621 range of species, including two Orthoptera species, Vos *et al.* (2001) found a
622 metapopulation viability threshold at 50% patch occupancy within the landscape. The
623 least-cost model (Scenario 3) therefore suggests that for wood cricket viable
624 metapopulation structures exist within the predicted occupied habitat networks. This
625 conclusion would not have been reached with the less detailed alternative models that
626 were developed (i.e. Scenario 1 and 2). Compared to these models, this indicates the
627 greater ability of the detailed model (Scenario 3) to indicate more precisely the areas
628 where functional metapopulation communities are likely to occur in the wider landscape
629 for wood cricket and similar species, making it more useful for forest managers and
630 practitioners.

631

632 The overall success of forest conservation lies in adopting a multi-scale and multi-
633 management strategic approach (Lindenmayer and Franklin, 2002). This research
634 showed that for making informed decisions, least-cost buffer approaches could
635 potentially be a valuable tool to assist and support forest and landscape conservation
636 management and planning. [It also showed that collection of field data is highly
637 necessary to generate valuable output and for the validation of these kind of models.](#)
638 However, where the availability of these data (i.e. species-specific as well as land
639 cover data) is generally limited and the quality often poor, least-cost modeling
640 approaches should be used with caution. Therefore, least-cost buffer-radius
641 approaches should be used as an indicative rather than prescriptive tool within the
642 existing management toolset. [Further modeling efforts should focus on incorporating
643 real data of multiple species taxa to improve their overall usefulness in assisting and
644 supporting landscape conservation and planning.](#)

645

646

647 **Acknowledgements**

648

649 We like to thank the Forestry Commission and the Scottish Forestry Trust for funding
650 this research. Furthermore, we like to thank the People's Trust for Endangered Species
651 (PTES) for providing us with the opportunity to work in their woodlands on the Isle of
652 Wight (UK).

653

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813

814

815

816 *Table 1: Summary of the landscape features that were included in the maps that were used for*
 817 *the different scenarios.*

Maps used	Scenario 1 Map 1	Scenario 2 Map 1 & 3	Scenario 3 Map 2 & 4
Landscape features	Included	Included	Included
Forest	yes	yes	yes
Arable and urban developed land	no	yes	yes
Semi-natural landscape features and grassland	no	yes	yes
Estuaries	no	yes	yes
Roads, inland water bodies and streams	no	no	yes

818

819

820 *Table 2: Summary of the input values used for the individual scenarios. Buffer distance and*
 821 *permeability are in meters. Perm.: Permeability = Buffer distance/Cost. Cost values indicated*
 822 *with an asterisk were primarily based on field observations.*

	Scenario 1		Scenario 2		Scenario 3	
Buffer distance	60		60		60	
Landscape feature	Cost	Perm.	Cost	Perm.	Cost	Perm.
Forest	1	60	1	60	1	60
Arable and urban developed land			30*	2	30*	2
Semi-natural landscape features and grassland			2*	30	2*	30
Estuaries			60*	1	60*	1
Roads, inland water bodies and streams					60*	1

823

824

825 *Table 3:* Input values used for the sensitivity analyses for the least-cost buffer Scenario 3. The
826 buffer distance used was 60 m.

827

Landscape feature	Series 1 Cost	Series 2 Cost	Series 3 Cost
Forest	1	1	1
Arable and urban developed land	30	30	3, 6, 30
Semi-natural landscape features and grassland	2	1, 2, 6	2
Estuaries	30, 40, 60, 120, 600	60	60
Roads, inland water bodies and streams	30, 40, 60, 120, 600	60	60

828

829

830 *Table 4: Summary of the differences between the number of forest habitat networks generated*
 831 *by the different scenarios used in this study.*

	Scenario 1	Scenario 2	Scenario 3
No. of networks for all forest fragments	284**	391**	532**
No. of networks for all surveyed fragments	43*	69*	97*
All unoccupied networks	30*	52*	75*
All occupied networks	13	17	22
No. of occupied fragments included	32	32	32
No. of unoccupied fragments included	59*	36*	24
Percentage of occupied fragments included	35%	47%	57%

832

833 * $P < 0.05$; ** $P < 0.001$. Based on chi-square test of number of networks between consecutive
 834 scenarios.

835

836

837 *Table 5: Results of the individual sensitivity analyses for Scenario 3. Series 1 varied the cost*
 838 *values for estuaries, roads, inland water bodies and watercourses. Series 2 varied the cost*
 839 *values for semi-natural landscape features and grassland. Series 3 varied the cost values for*
 840 *arable and urban developed land. Networks indicate the number of forest habitat networks*
 841 *generated with each model run.*

Series 1		Series 2		Series 3	
Cost	Networks	Cost	Networks	Cost	Networks
30	432	1	462*	2	512
40	433*	2	532*	3	519
60 (excl minor roads)	457*	6	595	6	532
60	532*				
120	532				
600	532				

842

843 * $P < 0.05$; Based on chi-square test of number of networks between consecutive cost values.

844

845

846 *Figure 1.* The predicted forest habitat networks on the Isle of Wight generated by the Euclidean
847 buffer-radius approach (a) Scenario 1 ($n = 284$); and the least-cost buffer-radius approach (b)
848 Scenario 2 ($n = 391$) and (c) Scenario 3 ($n = 532$). The patches with different shades of grey
849 represent the individual forest networks.
850

851 *Figure 2.* Detail showing the break-up of a forest network when using an increasing amount of
852 input data (Scenario 1 – 3, a-c respectively). The different shades of grey indicate individual
853 networks. Lines represent roads and small watercourses, and dark dots indicate inland water
854 bodies.

855

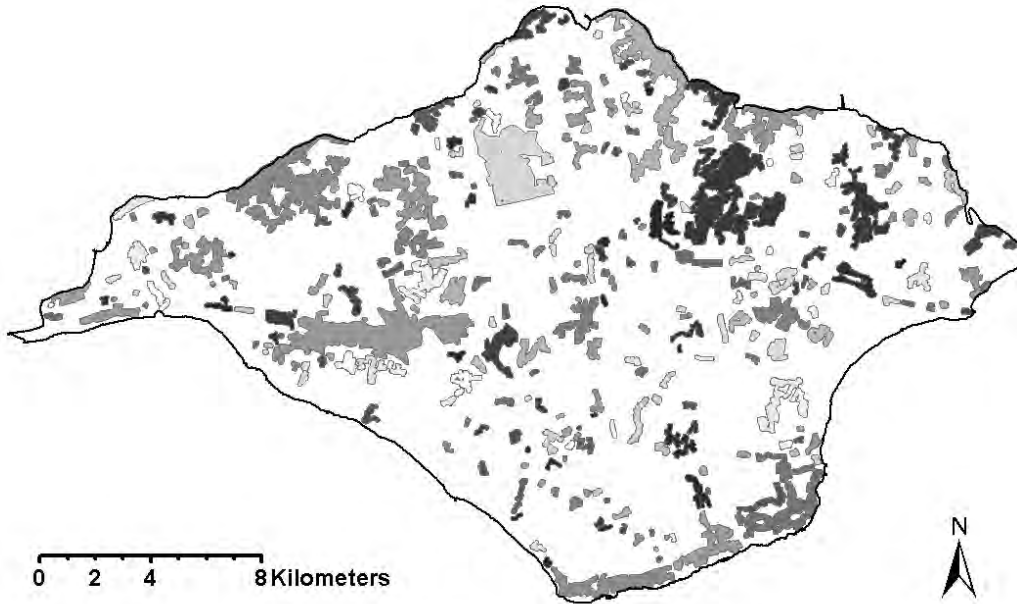
856

857 *Figure 3.* Frequency table for the predicted forest habitat networks generated by Scenarios 1, 2
858 and 3 (a, b and c respectively) grouped by network surface area. Graphs show an increase in
859 number of small networks, a decrease in number of large networks, and an overall decrease in
860 the size of the networks when increasing the amount of input data. * $P < 0.05$; ** $P < 0.001$,
861 based on Mann-Whitney U test of median network area between consecutive approaches.
862
863

864 *Figure 4.* The number of predicted forest habitat networks generated by Scenarios 1 – 3 with
865 increasing buffer distance (m).
866
867

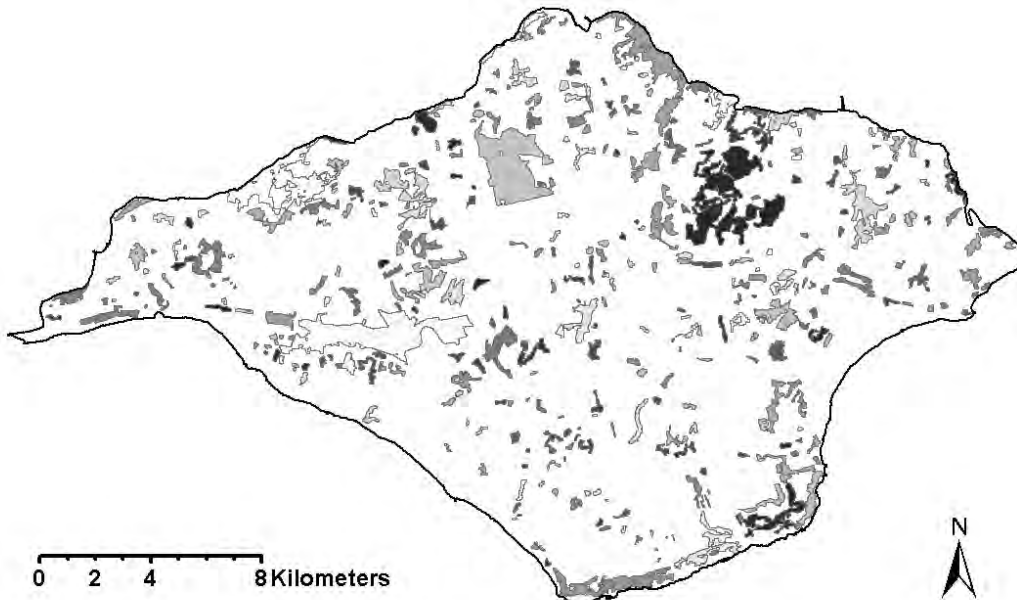
868 #Figure 1a-c#

869



870

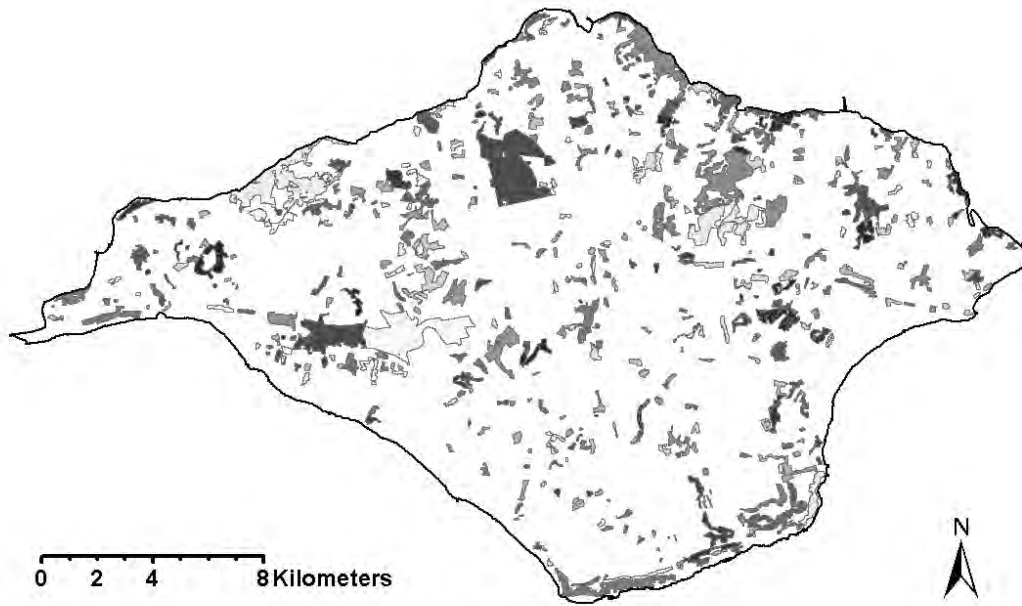
a



871

b

872



873

C

874

875

876 #Figure 2a-c#

877



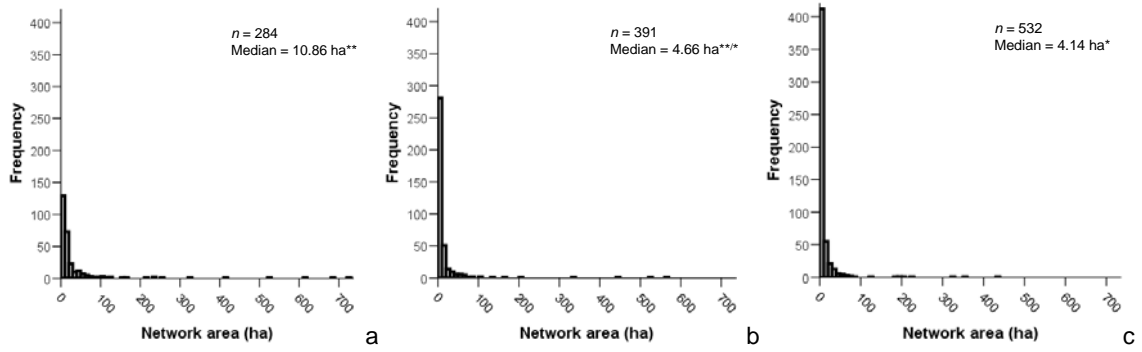
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881 #Figure 3a-c#

882

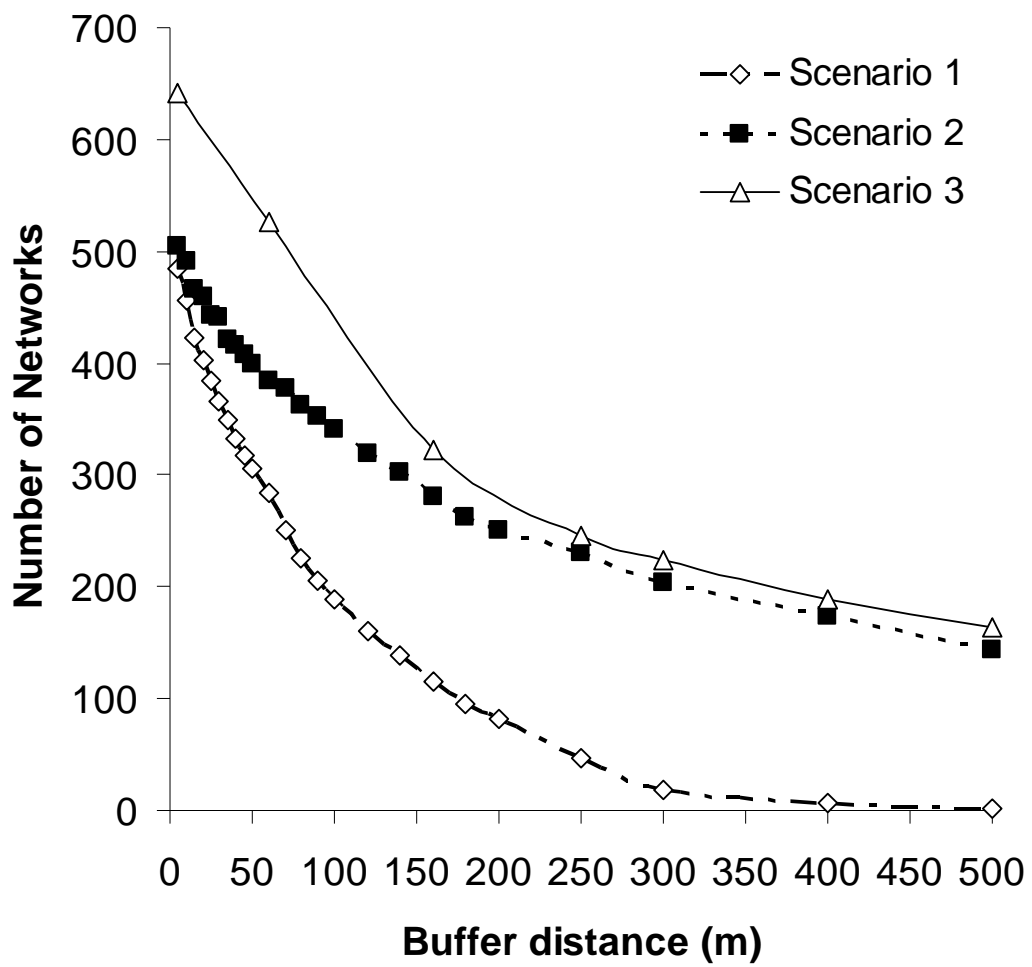


883

884

885 #Figure 4#

886



887