1   Predicting the vulnerability of reservoirs to poor water quality and

2   cyanobacterial blooms

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26 **Abstract**

27 Cyanobacterial blooms in drinking water reservoirs present a major ecosystem

28 functioning and human health issue. The ability to predict reservoir vulnerability to

29 these blooms would provide information critical for decision making, hazard

30 prevention and management. We developed a new, comparative index of vulnerability

31 based on simple measures of reservoir and catchment characteristics, rather than water

32 quality data, which were instead used to test the index's effectiveness. Testing was

33 based on water quality data collected over a number of seasons and years from 15

34 drinking water reservoirs in subtropical, southeast Queensland. The index correlated

35 significantly and strongly with algal cell densities, including potentially toxic

36 cyanobacteria, as well as with the proportions of cyanobacteria in summer months.

37 The index also performed better than each of the measures of reservoir and catchment

38 characteristics alone, and as such, was able to encapsulate the physical characteristics

39 of subtropical reservoirs, and their catchments, into an effective indicator of the

40 vulnerability to summer blooms. This was further demonstrated by calculating the

41 index for a new reservoir to be built within the study region. Under planned

42 dimensions and land use, a comparatively high level of vulnerability was reached

43 within a few years. However, the index score and the number of years taken to reach a

44 similar level of vulnerability could be reduced simply by decreasing the percentage of

45 grazing land cover via revegetation within the catchment. With climate change,

46 continued river impoundment and the growing demand for potable water, our index

47 has potential decision making benefits when planning future reservoirs to reduce their

48 vulnerability to cyanobacterial blooms.

49

50 **Key Words**

51 Agricultural land use, algae, climate change, decision making, eutrophication,

52 watershed

53

54 **1 Introduction**

55 In the tropics and subtropics, climate and the physical characteristics of reservoirs

56 create conditions that promote algal blooms (Jones and Poplawski 1998). Higher air

57 temperatures and longer daylight hours in summer months lead to stronger thermal

58 stratification and, potentially, the release of bioavailable nutrients from anoxic

59 sediments (Burford and O'Donohue 2006). Summer-dominated rainfall and

60 subsequent inflows also tend to increase nutrient supply during this time. Together

61 with the long water residence times typically associated with reservoirs, as opposed to

62 river systems, these factors can combine with other, complex causative factors to

63 make summer blooms a common phenomenon (McGregor and Fabbro 2000). Indeed,

64 there is growing concern over the increased reporting of toxic cyanobacterial blooms

65 in reservoirs the world over, particularly during summer months (e.g Padisák 1997;

66 Bouvy et al. 2000; Wiedner et al. 2007). In addition, global warming is predicted to

67 increase nutrient loads and algal growth in temperate systems (Matzinger et al. 2007;

68 Paerl and Huisman 2008).

69

70 Catchment (= watershed) characteristics are also associated with changes in water

71 quality and algal blooms within impounded systems. In particular, agricultural land

72 use can lead to reservoir eutrophication: 1) by increasing soil erosion and nutrient

73 loads in runoff, which can cause changes in nitrogen and phosphorus ratios; or 2)

74 through a combined effect with other catchment and reservoir characteristics, such as

75 water storage capacity and catchment size (Arbuckle and Downing 2001; Knoll et al.

76 2003; Davis and Koop 2006; Yang et al. 2008). Because summer conditions favour

77 algal blooms and, particularly in the tropics and subtropics, tend to occur in tandem

78 with increased precipitation (which increases the inflow of nutrients and sediments),

79 the effects of land use on reservoir water quality may be most apparent during warmer

80 months.

81

82 In response to the increased demand for irrigation and drinking water supply by

83 growing human populations, new reservoirs are being built and/or the storage

84 capacities of existing reservoirs increased (L'Vovich 1990; Pringle 2001; Zengi et al.

85 2007). In developing countries, particularly China and India, new reservoirs in both

86 urban and remote areas continue to be constructed (Dudgeon 2000). Much of this

87 reservoir expansion is occurring in the tropics and subtropics, and often in conjunction

88 with conversion of forest or savannah into agricultural lands (Blanch 2008; Gücker et

89 al. 2009). This combination of factors suggests that the incidence of algal blooms will

90 become more likely. In turn, there is a need to reliably forecast the occurrence and

91 frequency of toxic algal blooms in existing or future reservoirs.

92

93 Regular monitoring within drinking water reservoirs is conducted to ensure that the

94 relevant water quality guidelines for ecosystem and human health are met. This

95 process, and the supply of safe drinking water, however, consumes considerable

96 human and fiscal resources (De Ceballos et al. 1998). In addition, monitoring often

97 commences after reservoirs are built and water quality problems have begun to occur.

98 The ability to predict whether reservoirs may be more or less vulnerable to poor water

99 quality and toxic cyanobacterial blooms, and why, is critical for reliable hazard

100 prevention, planning and management. Therefore, our objectives were to develop an

101   index of vulnerability to poor water quality based on simple measures of reservoir and

102   catchment characteristics, and to test the index's ability to predict this vulnerability

103   using water quality and cyanobacteria data collected from 15 drinking water

104   reservoirs in subtropical southeast Queensland. We expected that an effective index

105   would show positive correlation with nutrients, chlorophyll a concentrations and algal

106   and cyanobacterial cell densities in summer months.

107

108   **2 Materials and methods**

109   *2.1 Study region*

110   The 15 reservoirs examined in this study supply drinking water to the urban and semi-

111   rural populations of southeast Queensland (*c*. 2.8 million) and vary in catchment size and

112   full supply capacity (Fig. 1, Table 1). In the past 30 years, average annual rainfall in the

113   region has ranged from 800 to 1600 mm (www.bom.gov.au). Land use in the catchments

114   is dominated by natural bushland and pastoral activities (mainly cattle grazing), with

115   smaller proportions of cropping and residential lands (Fig. 2).

116

117   *2.2 Index calculation*

118   Reservoir and catchment characteristics can be summarised by several parameters, many

119   of which have been examined for their ability to explain variation in reservoir water

120   quality (e.g. Forbes et al. 2008). The parameters we used to calculate the vulnerability

121   index (VI) satisfied the following four conditions: 1) correlation with water quality was

122   well established in the literature, either theoretically or empirically; 2) parameters were

123   easily calculated from readily available data on reservoir or catchments characteristics; 3)

124   parameters were not strongly correlated with each other (Spearman correlation, R < 0.70

125   and/or $P > 0.05$), and 4) parameters were relatively static or predictable through time so

126   that the index was unaffected by substantial spatial and temporal variation (e.g. this would

127 exclude parameters like nutrient concentrations and water transparency). This last

128 condition also ensured that the index was not self-forecasting (e.g. high nutrient

129 concentrations predicting that a reservoir was vulnerable to high nutrient concentrations).

130 Five parameters satisfied the conditions listed above and the VI, which ranges from 0

131 (lowest vulnerability) to 1 (highest vulnerability), was calculated as follows:

132

133 VI = (percentage grazing land cover[a] + reservoir shoreline to surface area ratio[bc] +

134 reservoir volume at full supply capacity[ab] + reservoir volume to catchment area ratio[bc] +

135 age since dam construction[ab])/ 5

136

137   a) Range standardised so that the highest value = 1 and the lowest = 0;

138   b) Log transformed to reduce skew;

139   c) Range standardised so that the highest ratio = 0 and the lowest = 1.

140

141 Log transformation and range standardisation gave each parameter an equivalent

142 weighting in the formula and created a comparative index of vulnerability among the 15

143 reservoirs.

144

145 *2.3 Index testing*

146 The ability of the index to predict the vulnerability of reservoirs to poor water quality

147 and algal blooms was assessed by testing the correlation between index scores and

148 water quality parameters in the 15 reservoirs. Each reservoir was sampled once between

149 9 February and 3 March 2009 in the late summer period. Over the past 30 years in the

150 study area, mean rainfall and temperature during February has been 100-300 mm and 18-

151 27 °C (min-max ranges, www.bom.gov.au). Heavy rainfall was experienced while

152 sampling Kurwongbah reservoir and this rain event caused overflow at the dam walls of

153 both Kurwongbah and Somerset at the time of sampling. There was also a bloom of the

154 toxic cyanobacterium *Cylindrospermopsis raciborskii* in Borumba reservoir during

155 sampling. Three reservoirs had destratification units in use near the dam wall to vertically

156 mix the water: Leslie Harrison, Macdonald and North Pine (see Burford and O'Donohue

157 2006).

158

159 At least three sites were sampled in each reservoir. Sites were near the dam wall, mid-

160 reservoir, and in the upstream section of each reservoir. Sampling was conducted at the

161 deepest point of each site, which was at least 6 m (except for the upstream sites at

162 Kurwongbah and Little Nerang which were 2-4 m in depth). Four sites were sampled in

163 the larger reservoirs (e.g. Somerset) and in those with two major arms (Borumba, Hinze,

164 Leslie Harrison and North Pine). In Wivenhoe, the largest reservoir out of the 15, only

165 three sites were sampled due to an aquatic weed infestation restricting access to the most

166 upstream reaches; however, the three sites were still representative of dam wall, mid-

167 reservoir and upstream locations.

168

169 At each site, a 3 m depth-integrated sample of surface water was collected with a

170 modified PVC pipe. Bottom water was collected with a van Dorn (3.2 L Vertical Beta

171 Plus) sampler from 1 m above the bottom of each site. Surface and bottom water were

172 each transferred to a clean bucket from which samples for water quality analyses were

173 taken. Each process was repeated to obtain duplicate samples.

174

175 Surface water was subsampled for analyses of total nitrogen and phosphorus (TN, TP; for

176 both whole and dissolved fractions), dissolved inorganic nitrogen and phosphorus (DIN

177 and DIP), and chlorophyll *a* (Chl) concentrations as well as algal identification and cell

178 densities (cells mL^{-1}), including potentially toxic cyanobacterial species (*Anabaena*

179 *circinalis*, *A. bergii*, *Aphanizomenon ovalisporum*, *C. raciborskii* and *Microcystis*

180 *aeruginosa*). Bottom water subsamples were analysed for these same parameters,

181 excluding chlorophyll *a* concentration and algal identification. All subsamples that were

182 analysed for dissolved fractions were pre-filtered, *in situ*, through 0.45-μm membrane

183 filters (Millipore) and subsamples for algal identification were fixed with Lugol's iodine

184 solution (0.6 % final concentration). Concentrations of dissolved organic nutrients (DON

185 and DOP) were determined by subtraction (e.g. DON = dissolved TN fraction – DIN). All

186 samples were stored in the dark and on ice until transported to the laboratory.

187

188 Nutrient analyses were conducted following standard colorimetric methods; chlorophyll *a*

189 was extracted in 100% acetone and measured spectrophotometrically (American Public

190 Health Association, 1995). DIN and DIP concentrations were often near or at detection

191 limit (0.002 mg L^{-1}) and were not used in further analyses. Algal taxa were identified to

192 species level, where possible, under 400x phase-contrast microscopy and cells were

193 counted using a Sedgewick Rafter counting chamber (Lund et al. 1958; Burford et al.

194 2007).

195

196 The top layer (*c.* 2 cm) of sediments at the bottom of each site was collected in duplicate

197 using a weighted sediment corer. These samples were analysed for TN and TP

198 concentrations as well as stable carbon and nitrogen isotope ratios (δ^{13}C and δ^{15}N ‰),

199 which were determined using a mass spectrometer (GV Isoprime, Manchester, UK),

200 following standard methods (American Public Health Association 1995; Jardine et al.

201 2003).

202

203 Data was subjected to Spearman's rank correlation as this test handles parameters with

204 skewed distributions and/or heteroskedacity, which included the majority of the water

205 quality parameters used in the analysis as well as the VI itself. Statistical significance was

206 recorded at $P < 0.05$ and tests were conducted within the R stats package (www.r-

207 project.org/). The strength (size of the correlation coefficient, R) and significance of

208 correlations between VI and water quality parameters were also compared with those

209 between the individual VI (grazing, shore:SA, Vol, Vol:CA, age) and water quality

210 parameters.

211

212 Data from a previous study on 7 of the 15 reservoirs were also used as an independent

213 dataset to assess the VI's effectiveness (Burford et al. 2007). In this study, water

214 quality was assessed at two sites (dam wall and upstream) in each reservoir during

215 spring (October 2004), early summer (December 2004), late summer (February 2005)

216 and autumn (April 2005). Correlations between these data and the VI were tested

217 using the same methods outlined for the February 2009 study, with the VI calculated

218 based on reservoir age in 2004 and 2005 for the corresponding years of sampling.

219

220 **3 Results**

221 *3.1 Water quality and algal cell densities (Feb 2009)*

222 Mean surface water temperatures, integrated over the top 3 m, ranged from 26.7 ± 0.5

223 °C at Baroon reservoir to 28.7 ± 0.7 °C at Moogerah. The exception was Little Nerang

224 reservoir, which had a mean surface water temperature of 22.5 ± 1.8 °C. Within each

225 reservoir, TN and TP concentrations were generally higher in bottom waters than

226 surface waters (see Accessory Publication). Borumba, Moogerah and Manchester had

227 the highest mean concentrations of TN, in both surface (0.66-0.88 mg L^{-1}) and bottom

228 waters (1.18-1.31 mg L^{-1}). TP concentrations were similar among most reservoirs;

229 mean concentrations were all < 0.05 mg L^{-1} except for the bottom waters of Borumba,

230   Somerset, Wivenhoe, Maroon and Moogerah (0.135-0.372 mg L^{-1}). Many reservoirs

231   had high proportions of DON in surface waters and high mean concentrations of DOP

232   were found in bottom waters of Borumba, Wivenhoe, Somerset, Maroon and

233   Moogerah (0.094-0.271 mg L^{-1}).

234

235   The algal composition of surface water samples from all reservoirs, in terms of mean

236   cell densities, was dominated by cyanobacteria (Fig. 3; Accessory Publication).

237   Borumba had the highest mean algal cell density of all reservoirs (455 000 ± 91 000

238   cells mL^{-1}), followed by Moogerah, Somerset and Wivenhoe (means > 200 000 cells

239   mL^{-1}). Hinze had the lowest mean algal cell density (20 000 ± 5 000 cells mL^{-1}).

240   Potentially toxic cyanobacteria, when present within reservoirs, were most often

241   dominated by *C. raciborskii*. The exceptions were Hinze (mid-reservoir only) and

242   Maroon, in which *Anabaena circinalis* dominated. Five reservoirs had no potentially

243   toxic cyanobacterial species identified (Cooloolabin, Macdonald, Ewen Maddock,

244   Leslie Harrison and Little Nerang).

245

246   *3.2 Index of vulnerability (VI)*

247   Based on the index calculation outlined in the Methods, Wivenhoe reservoir had the

248   highest level of vulnerability to poor water quality and algal blooms (VI = 0.77), followed

249   closely by Somerset (0.74) and Moogerah (0.67) (Fig. 4). Cooloolabin had the lowest VI

250   (0.18). Ewen Maddock (0.29), Little Nerang (0.30), Hinze (0.33) and Leslie Harrison

251   (0.36) also had low indices. The remaining reservoirs had intermediate VI scores

252   (Macdonald = 0.43, Manchester = 0.44, Baroon = 0.46, Maroon = 0.48, Kurwongbah and

253   North Pine = 0.50, Borumbah = 0.52).

254

255 *3.3 Index performance*

256 Statistically significant correlations between water quality parameters and the VI

257 scores were all positive (Table 2). These correlations were also stronger and more

258 often statistically significant than the correlations between water quality parameters

259 and each of the five parameters used to calculate the VI (Table 3). Significant

260 correlations were found between the VI and both the densities and proportions of algal

261 cells in all study periods, except October 2004 (early spring) for which correlations

262 were all non-significant. Among the significant correlations, the strongest were with

263 total algal and cyanobacterial cell densities, and the strongest of these were found in

264 February 2009 (R = 0.82 and 0.83) and December 2004 (R = 0.86 and 0.86).

265 Correlations with the proportion of cyanobacterial cells were strongest during the

266 2004-5 study (R = 0.74-0.82). February was the only month for which significant

267 correlations with potentially toxic species were detected (2005: R = 0.69 for density

268 only; 2009: R = 0.71 and 0.64 for density and proportion respectively). This was also

269 the case for chlorophyll *a* concentrations (February 2005, R = 0.56; February 2009, R

270 = 0.41). In addition, correlations with nutrient concentrations measured in all months

271 (water column TN and TP) were only significant in February 2009 (except for surface

272 TN in December 2004; R = 0.55) and the strongest was with TP in bottom waters (R =

273 0.82). The VI also correlated well with sediment nutrient and carbon data, in

274 particular with $\delta^{13}C$ (R = 0.72), which were measured in February 2009 only.

275

276 **4 Discussion**

277 The index of vulnerability to poor water quality and algal blooms correlated strongly

278 and significantly with algal cell densities, including potentially toxic cyanobacteria,

279 and the proportions of cyanobacteria within the subtropical reservoirs during summer

280 months. Cyanobacteria are capable of regulating their buoyancy, surviving low light

281 conditions, storing nutrients and utilising forms of nutrient that are inaccessible to

282 other taxa, all of which allows them to dominate the algal community under various

283 physicochemical conditions (Padisák 1997; Burford et al. 2006; Posselt et al. 2009).

284 Given this flexibility, the ability of the VI to reflect increased summer densities and

285 proportions of cyanobacteria, based on physical characteristics of the reservoirs and

286 catchments alone, suggests that it may be more capable of assessing bloom

287 susceptibility than traditional measures based on nutrient concentrations, trophic

288 status or light availability (e.g. Downing et al. 2001). Our index also performed better

289 than each of the VI parameters alone, which further supported its ability to

290 comparatively assess the reservoirs' vulnerability. Overall, our analyses suggest that

291 strong links exist among the physical environment of dammed river systems, their

292 physicochemical characteristics and algal ecology, although further work is required

293 to understand and show causality.

294

295 Land use, particularly animal agriculture, has been implicated in the eutrophication of

296 streams, rivers, lakes and reservoirs the world over (Søndergaard and Jeppesen 2007). In

297 our study of subtropical reservoirs, 12 out of the 18 water quality parameters analysed

298 showed significant correlation with the percentage of grazing land cover in the reservoirs'

299 catchments. Reservoirs with lower reservoir volume to catchment area ratios are more

300 likely to have stronger links with catchment characteristics, including land use and the

301 consequent reduction in water quality, than those with higher ratios, regardless of climatic

302 zone (cf. Burford et al. 2007). Indeed, lower ratios have been linked with higher

303 concentrations of chlorophyll *a* and total phosphorus in temperate-zone reservoirs, Ohio

304 USA (Knoll et al. 2003).

305

306 Physical characteristics of reservoirs also affect internal water quality. For example,

307 increased water residence time, through the increased net loading of nutrients in

308 reservoirs, has long been implicated in the promotion of algal blooms and reduced water

309 quality (Søballe and Kimmel 1987; Harris 2001). We did not include this parameter in our

310 index, however, as the data needed to calculate residence time was not available for all

311 reservoirs. In addition, water levels in the reservoirs fluctuate through time due to

312 variation in inflow and outflow volumes and timing, such that residence time is not

313 constant. Rather, we used age since completion of the dam wall as an alternative indicator

314 of the nutrient loading capacity of reservoirs. Older reservoirs were assumed to have

315 increased stores of nutrients, and strong correlations between nutrient concentrations in

316 the water column and reservoir age were found. The specific processes linking reservoir

317 age to present-time water quality are not clear; however, it may be that as reservoirs age,

318 sediment loading into reservoirs results in siltation and reduced water depth, particularly

319 in the upper reaches. Nutrients released from sediments would therefore be more readily

320 available for algal growth in surface waters, consistent with increased benthic-pelagic

321 coupling (see also Nõges et al. 1999).

322

323 In addition, our index was based on the ratio of reservoir shoreline length to surface area.

324 Reservoirs with lower ratios (shoreline length to surface area or reservoir volume) are

325 likely to have a stronger pelagic and hypolimnic influence on reservoir water quality and

326 ecosystem processes than those with higher ratios (Wetzel 2001). For the tropics and

327 subtropics in particular, reservoirs that have a greater proportion of pelagic than littoral

328 habitat may become more susceptible to poor water quality when internal processes, such

329 as stratification and sediment remineralisation, start to affect water quality in the summer

330 months (Jones and Poplawski 1998).

331

13

332   The combination of these parameters (percentage grazing, shoreline to surface area

333   ratio, reservoir volume, volume to catchment area ratio and reservoir age) produced a

334   good index of vulnerability to poor water quality and algal blooms in the subtropical

335   reservoirs, and in particular, to increased cyanobacterial densities and proportions in

336   summer months. Correlation between the VI and pre-summer water quality (Oct

337   2004) was not detected. Algal composition during this month was significantly

338   different to summer and post-summer months (Burford and Donohue 2006; Burford et

339   al. 2007) and recent studies of Wivenhoe reservoir suggest that this pre-

340   summer/summer difference may be expected for other reservoirs in the study region

341   (P. Muhid, unpublished results). As expected, correlations were highly significant in

342   summer months (Dec 2004, Feb 2005, Feb 2009), which included both small (n= 14)

343   and larger (n = 42-50) datasets. The index also showed positive correlation with

344   nutrient concentrations and/or stable isotope ratios in the water column and sediments

345   measured during the 2009 summer sampling period. Warm temperatures and

346   stratification can lead to sediment remineralisation and the renewed availability of

347   nutrients to cyanobacteria. In addition, enriched carbon and nitrogen isotope ratios in

348   reservoirs have been linked to increased autotrophic production (for carbon) and inputs of

349   nitrogen associated with agricultural or urban land use (Leavitt et al. 2006; Wu et al.

350   2006; Tomaszek et al. 2009).

351

352   In summary, our analysis indicated that the VI may be useful for assessing summer

353   bloom vulnerability in subtropical reservoirs. However, the link between summer

354   rainfall and reservoir water quality, like that with summer temperatures, was inherent

355   in the reasoning behind the index. Southeast Queensland experienced drought

356   conditions (minimum summer rainfall) between *c*. 2002 and December 2009. In

357   conjunction with summer temperatures, the recent rainfall and inflow events prior to

358   the February 2009 sampling period, although not substantial, may have improved the

359   VI's performance in comparison with the other sampling periods, including February

360   2005. As such, the risk of summer bloom events in reservoirs with high index scores

361   may decrease in drought conditions. However, if water depth declines to a critical

362   threshold where sediment remineralisation processes promote algal growth throughout

363   the water column, summer blooms may be inevitable (P. Muhid, unpublished results),

364   particularly given the known effect of increased temperatures on algal growth.

365

366   The ultimate aim of the VI is to provide water authorities and managers with a rapid

367   tool to confidently assess how vulnerable a reservoir is (or may be) to poor water

368   quality, and in particular, cyanobacterial blooms. For example, we applied the index

369   to a new dam (Wyaralong) being constructed about 20 km northeast of Maroon

370   reservoir, to compare its potential vulnerability with the 15 reservoirs examined above

371   (Fig. 5). Construction is scheduled for completion by end 2011. Based on planned

372   dimensions and current grazing cover (46.9%), Wyaralong's VI (0.55) predicts mid-

373   range vulnerability, comparative with reservoirs like Maroon and Kurwongbah, for at

374   least 5 years after competition (Table 1, Fig. 5). However, 10 years after completion,

375   the VI is more comparable with that of Baroon, and 20 years after completion with

376   Borumbah and North Pine. After 100 years, the VI is at the higher end of vulnerability

377   to eutrophication and cyanobacterial blooms, such that Wyaralong is the fourth most

378   vulnerable reservoir with respect to Moogerah, Somerset and Wivenhoe (Fig. 5).

379

380   A simple exercise in decreasing or increasing the percentage of grazing land cover in

381   Wyaralong's catchment by 10% via reforestation, predicts that the VI will either reach

382 the same endpoint (the fourth most vulnerable reservoir) after only 5 years (+ 10%

383 grazing cover) or remain below this point for at least 100 years (- 10% grazing cover)

384 (all other parameters except age were unchanged for all reservoirs; Fig. 5). This

385 demonstrates that the VI could provide input to the planning of new reservoirs and

386 assist in decision making about investment to mitigate for adverse water quality

387 outcomes. This may include such comparisons as costs of land use change versus

388 increased treatment and may lead to the expansion of impact assessments to include

389 the possibility of new reservoirs meeting water quality targets and to consider the

390 potential impacts of algal blooms.

391

392 Our paper encapsulates the physical characteristics of a group of reservoirs and their

393 catchments into an effective indicator of the potential for summer blooms and water

394 quality issues. However, the ability of the VI to predict the comparative susceptibility

395 to summer blooms of cyanobacteria and eutrophic conditions was assessed for a

396 limited number of reservoirs and in the subtropics alone. Adaptations may be required

397 to achieve an acceptable level of correlation between the VI and water quality

398 parameters in any one set of reservoirs (e.g. using residence time instead of reservoir

399 age to calculate the index). To confirm the generic usefulness of the VI, similar tests

400 are recommended in other reservoirs within subtropical, tropical and even temperate

401 climates.

402

403 **5 Conclusions**

404 • This is the first index to encapsulate the physical characteristics of subtropical

405 reservoirs and their catchments into an effective indicator of summer bloom

406 vulnerability.

407   • The index of vulnerability to poor water quality and cyanobacterial blooms in

408   the subtropical reservoirs examined in this study was based on the percentage

409   of agricultural land use in catchments and physical characteristics of

410   reservoirs.

411   • The index correlated strongly with increased cyanobacterial cell densities in

412   summer months, as well as their proportional contribution to the total algal

413   density.

414   • The index has the capability to predict vulnerability to poor water quality and

415   summer blooms of cyanobacteria in subtropical, and potentially, tropical and

416   temperate-zone reservoirs. With climate change, continued river impoundment

417   and the growing demand for potable water, our index may provide decision

418   making support when planning reservoirs, in the subtropics and elsewhere, to

419   reduce their vulnerability to cyanobacterial bloom events.

420

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570

571   **Figure captions**

572   Figure 1: Dam wall locations of 15 reservoirs (closed triangles) in subtropical

573   southeast Queensland, Australia, sampled during late summer 2009, and a new

574   reservoir currently in construction (open triangle), shown with catchment boundaries

575   of the major river systems in which the reservoirs are located.

576

577   Figure 2: Proportions of different land use cover in the catchments of 15 reservoirs.

578   See Table 1 for the key to reservoir coding.

579

580   Figure 3: Algal densities (cells mL^{-1}) within reservoirs (means with standard errors as

581   bars) sampled in February 2009. Potentially toxic cyanobacteria include *Anabaena*

582   *circinalis*, *Aphanizomenon ovalisporum*, *Cylindrospermopsis raciborskii* and

583   *Microcystis aeruginosa*.

584

585   Figure 4: Vulnerability Index for 15 reservoirs in subtropical Queensland (based on

586   ages of reservoirs in 2009). See Table 1 for the key to reservoir coding.

587

588   Figure 5: Vulnerability Index for 16 reservoirs in subtropical Queensland, at one, five,

589   twenty and one hundred years since the planned completion of Wyaralong dam wall

590   in 2011, given: the current percentage of grazing land cover in Wyaralong catchment

591   (top row); minus 10% (middle row); plus 10% (bottom row). Unbroken arrows show

592   the change in the level of among-reservoir vulnerability between grazing cover

593   scenarios. Broken arrows show the change in among-reservoir vulnerability through

594   time. See Table 1 for the key to reservoir coding.

595

Table 1: Physical characteristics of 16 subtropical reservoirs and their catchments.

Code	Reservoir	Shore (km)	SA (km^2)	Vol (ML)	Shore:SA (km^{-1})	Shore:Vol (km-2)	Depth (m)	Age (y)	CA (ha)	Vol:CA (ML ha^{-1})
Bar	Baroon	25.5	3.9	61000	6.6	4.2	15.7	21	6530	9.3
Bor	Borumba	44.5	3.8	46000	11.9	9.7	12.2	46	46900	1.0
Cool	Cooloolabin	12.8	1.4	14200	8.9	9.0	9.9	30	736	19.3
Ewen	Ewen Maddock	14.3	2.3	16600	6.4	8.6	7.4	27	2130	7.8
Hin	Hinze	67.4	9.3	163000	7.2	4.1	17.5	20	17600	9.3
Kur	Kurwongbah	33.4	3.4	14400	9.9	23.3	4.2	40	5250	2.7
LHD	Leslie Harrison	34.5	4.2	24800	8.2	13.9	5.9	25	8890	2.8
LNer	Little Nerang	10.9	0.6	9280	19.6	11.8	16.6	48	3600	2.6
Mac	Macdonald	38.3	2.6	8000	14.7	47.9	3.1	29	4960	1.6
Man	Manchester	27.3	2.6	26000	10.5	10.5	10.0	93	7260	3.6
Mar	Maroon	17.9	3.3	44300	5.4	4.0	13.3	35	10500	4.2
Moog	Moogerah	29.3	7.7	83800	3.8	3.5	10.9	48	22700	3.7
NPD	North Pine	167	21.2	215000	7.9	7.8	10.1	33	34900	6.2
Som	Somerset	237	39.7	369000	6.0	6.4	9.3	56	133000	2.8
Wiv	Wivenhoe	462	110	1150000	4.2	4.0	10.5	25	568000	2.0
Wya	Wyaralong	110	1.1	103000	9.0	10.8	8.4	-	54590	1.9

Shore, shoreline perimeter; SA, reservoir surface area at full supply level (FSL); Vol, water storage capacity at FSL; Depth (mean) = Vol/SA; Age, age to 2009 since the completion of dam construction; CA, catchment area; -, Wyaralong dam due for completion in 2011.

601 Table 2: Correlation between the VI and water quality parameters (mg L^{-1} unless otherwise indicated) within 15 subtropical reservoirs. Bold text
602 indicates significant correlations ($P < 0.05$).

		Oct 2004*			Dec 2004*			Feb 2005*			Apr 2005*			Feb 2009		
		R	P	n	R	P	n	R	P	n	R	P	n	R	P	n
Algae (cells mL^{-1})	S	0.14	0.6727	14	**0.86**	0.0001	14	**0.73**	0.0027	14	**0.61**	0.0010	14	**0.82**	<0.0001	50
Cyano (cells mL^{-1})	S	0.10	0.7633	14	**0.86**	0.0001	14	**0.75**	0.0019	14	**0.59**	0.0013	14	**0.83**	<0.0001	50
Cyano (%)	S	0.10	0.7175	14	**0.74**	0.0023	14	**0.76**	0.0015	14	**0.68**	0.0003	14	**0.37**	0.0064	50
Toxic (cells mL^{-1})	S	0.20	0.5014	14	0.20	0.4797	14	**0.69**	0.0061	14	0.00	0.9400	14	**0.71**	<0.0001	50
Toxic (%)	S	0.35	0.2293	14	0.00	0.9758	14	0.44	0.1205	14	0.03	0.5543	14	**0.64**	<0.0001	50
Chl (µg L^{-1})	S	0.17	0.5621	14	0.28	0.3260	14	**0.56**	0.0394	14	0.03	0.5634	14	**0.41**	0.0028	50
TN	S	0.51	0.0652	14	**0.55**	0.0414	14	0.50	0.0676	14	0.22	0.0933	14	**0.66**	<0.0001	50
TN	B	0.33	0.2520	14	0.40	0.1574	14	0.10	0.7743	14	0.03	0.5861	14	**0.50**	0.0002	49
TN (mg kg^{-1})	Sed			0			0			0			0	0.10	0.4905	48
TP	S	0.30	0.3017	14	0.10	0.7515	14	0.10	0.7978	14	0.01	0.7504	14	**0.50**	0.0002	50
TP	B	0.17	0.5856	14	0.33	0.2386	14	0.26	0.3747	14	0.13	0.2018	14	**0.82**	<0.0001	49
TP (mg kg^{-1})	Sed			0			0			0			0	**0.51**	0.0002	48
DON	S			0			0			0			0	**0.55**	<0.0001	50
DON	B			0			0			0			0	**0.28**	0.0454	49
DOP	S			0			0			0			0	0.10	0.4886	50
DOP	B			0			0			0			0	**0.66**	<0.0001	49
$\delta^{13}C$ (‰)	Sed			0			0			0			0	**0.72**	<0.0001	42
$\delta^{15}N$ (‰)	Sed			0			0			0			0	**0.57**	<0.0001	42

603 * Raw data sourced from a previous study (Burford et al. 2007). Cyano, cyanobacteria; Toxic, potentially toxic cyanobacteria; S, surface; B, bottom; Sed, sediment.
604

605 Table 3: A comparison of correlation between the VI versus individual physical parameters and water quality within 15 subtropical reservoirs
606 sampled in February 2009. Bold text indicates significant correlations ($P < 0.05$).

|			Grazing		Shore:SA		Vol		Vol:CA		Age		VI	
		n	R	*P*	R	*P*	R	*P*	R	*P*	R	*P*	R	*P*
Algae (cells mL^{-1})	S	50	**0.41**	0.0029	-0.26	0.0698	**0.53**	0.0001	**-0.47**	0.0006	**0.51**	0.0001	**0.83**	0.0000
Cyano (cells mL^{-1})	S	50	**0.47**	0.0006	**-0.35**	0.0115	**0.56**	0.0000	**-0.41**	0.0028	**0.45**	0.0009	**0.83**	0.0000
Cyano (%)	S	50	**0.47**	0.0007	**-0.65**	0.0000	**0.36**	0.0108	0.10	0.4764	0.04	0.8083	**0.38**	0.0064
Toxic (cells mL^{-1})	S	50	**0.34**	0.0163	-0.06	0.6921	**0.50**	0.0002	-0.26	0.0733	**0.35**	0.0126	**0.70**	0.0000
Toxic (%)	S	50	**0.32**	0.0255	0.00	0.9992	**0.44**	0.0015	-0.22	0.1319	**0.29**	0.0389	**0.64**	0.0000
Chl (µg L^{-1})	S	50	0.14	0.3237	**0.36**	0.0095	0.05	0.7532	**-0.62**	0.0000	**0.57**	0.0000	**0.41**	0.0028
TN (mg L^{-1})	S	50	0.17	0.2276	-0.05	0.7136	0.22	0.1023	**-0.48**	0.0005	**0.53**	0.0001	**0.66**	0.0000
TN (mg L^{-1})	B	49	-0.04	0.7829	-0.18	0.2004	0.23	0.1265	-0.19	0.1779	**0.67**	0.0000	**0.50**	0.0002
TN (mg kg^{-1})	Sed	48	-0.07	0.6491	0.11	0.2628	**0.48**	0.0004	-0.03	0.8373	0.25	0.0854	-0.10	0.4905
TP (mg L^{-1})	S	50	**0.46**	0.0008	0.04	0.7591	0.17	0.2404	**-0.50**	0.0002	**0.33**	0.0185	**0.50**	0.0002
TP (mg L^{-1})	B	49	**0.59**	0.0000	**-0.42**	0.0025	**0.53**	0.0001	**-0.39**	0.0050	**0.38**	0.0064	**0.82**	0.0000
TP (mg kg^{-1})	Sed	48	**0.42**	0.0026	**-0.47**	0.0000	**0.48**	0.0004	-0.03	0.8373	0.08	0.5665	**0.51**	0.0002
DON (mg L^{-1})	S	50	0.05	0.7519	-0.09	0.5319	0.14	0.3189	**-0.35**	0.0117	**0.50**	0.0002	**0.55**	0.0000
DON (mg L^{-1})	B	49	0.16	0.2744	-0.02	0.8914	0.04	0.7948	-0.24	0.0914	0.19	0.6229	**0.28**	0.0454
DOP (mg L^{-1})	S	50	**0.28**	0.0456	-0.26	0.0677	0.03	0.8251	-0.15	0.2946	0.07	0.1820	0.10	0.4886
DOP (mg L^{-1})	B	49	**0.47**	0.0005	**-0.39**	0.0056	**0.50**	0.0002	**-0.29**	0.0379	**0.31**	0.0260	**0.66**	0.0000
δ^{13}C (‰)	Sed	42	**0.74**	0.0000	**-0.28**	0.0043	**0.44**	0.0015	-0.12	0.3963	0.10	0.5050	**0.72**	0.0000
δ^{15}N (‰)	Sed	42	**0.62**	0.0000	**-0.38**	0.0061	**0.71**	0.0000	0.10	0.4861	-0.22	0.1282	**0.58**	0.0000

607 Cyano, cyanobacteria; Toxic, potentially toxic cyanobacteria; S, surface; B, bottom; Sed, sediment.
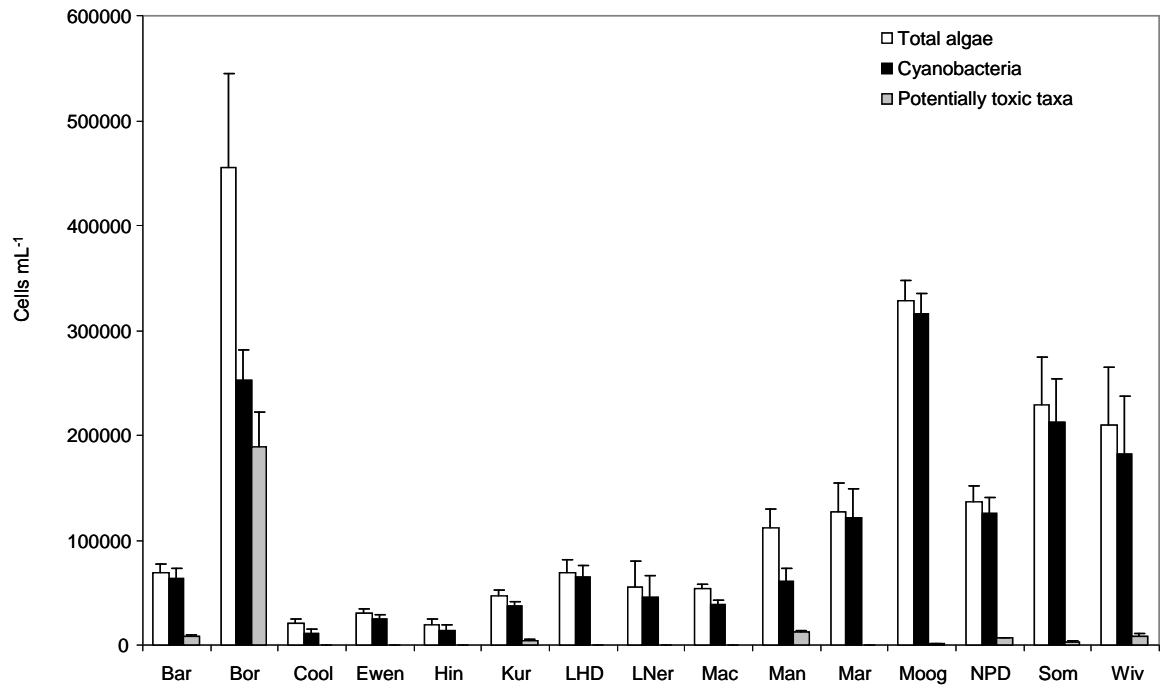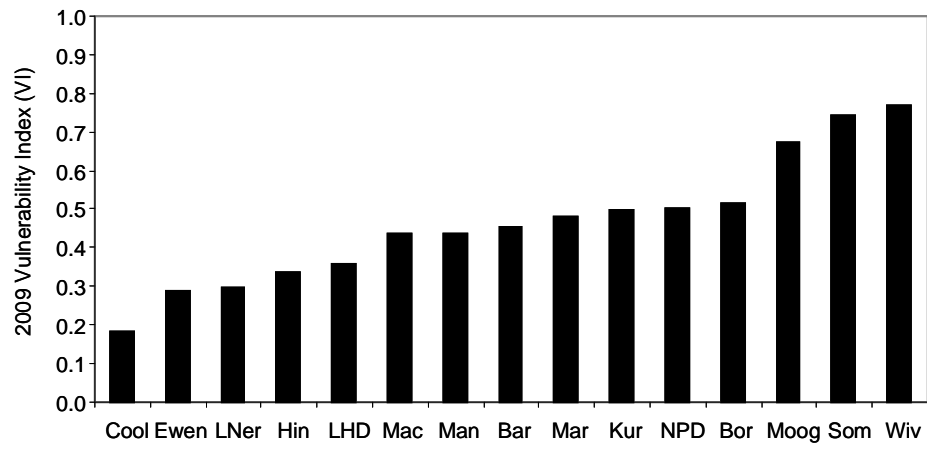608
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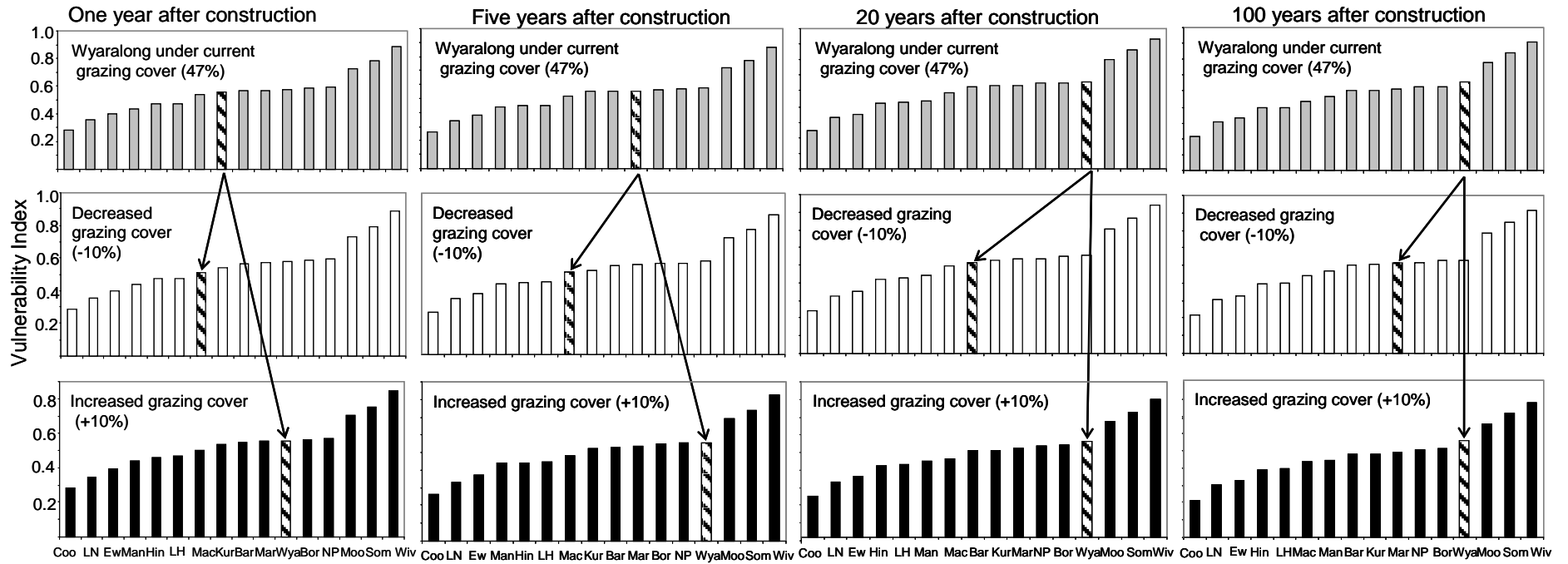611 **Figure 1**
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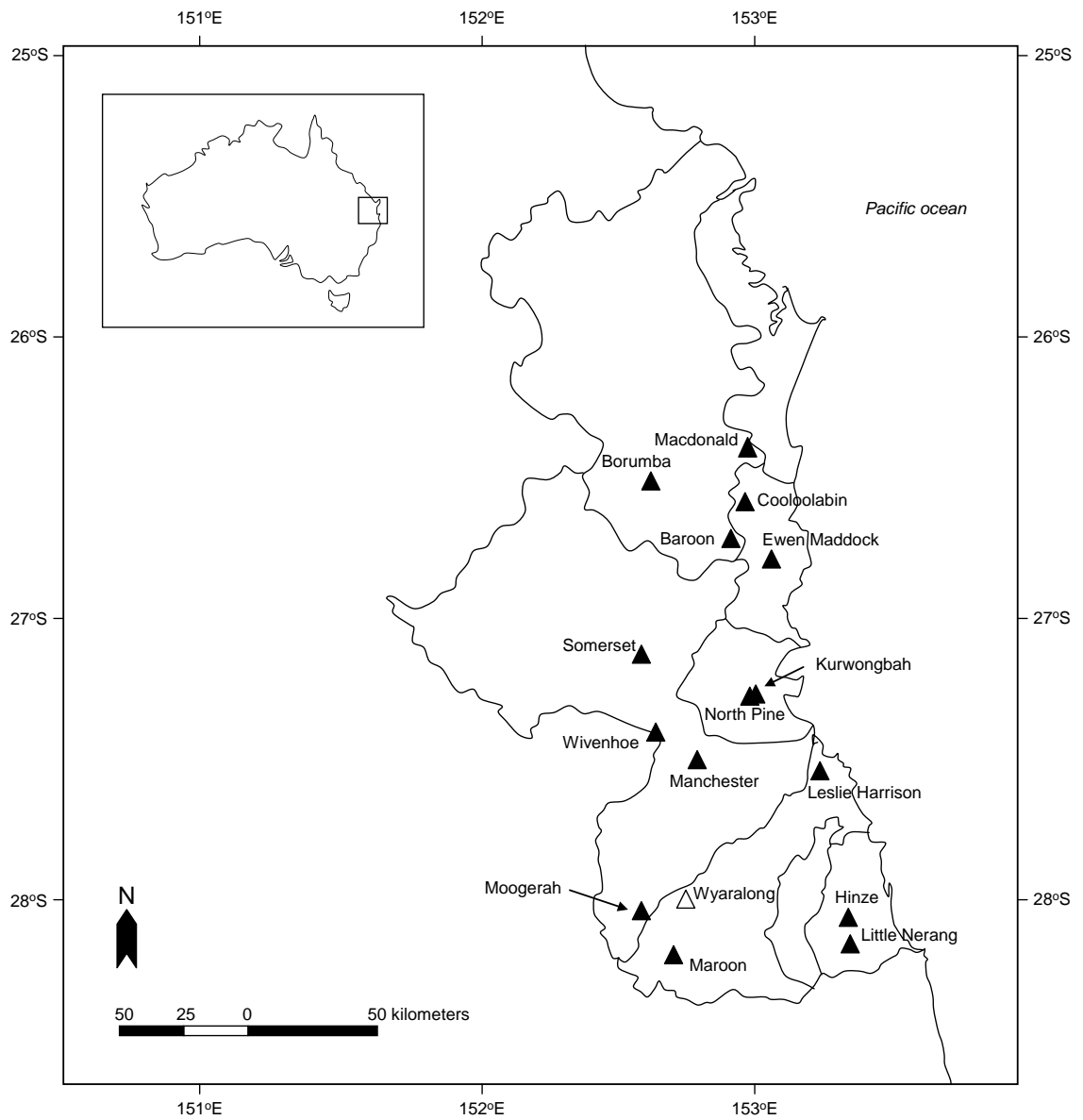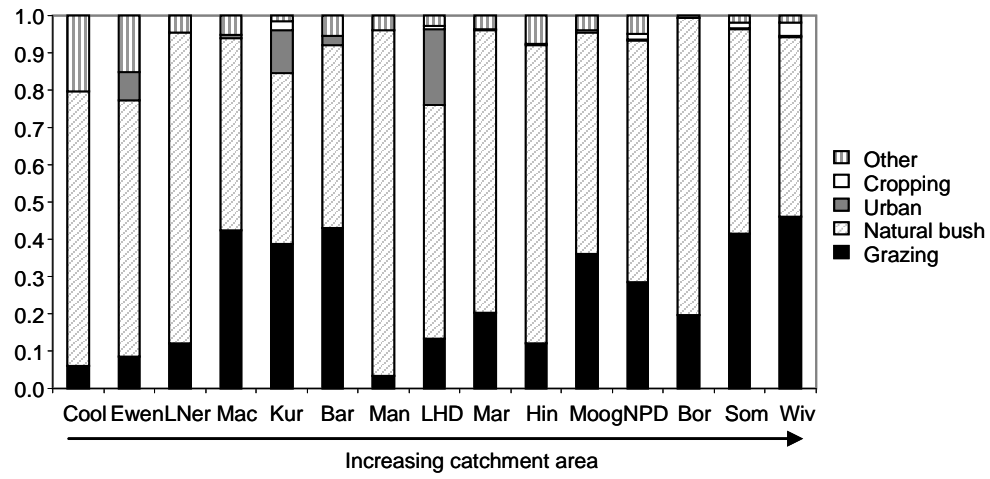
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620 **Figure 4**

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