Scenarios of land use and land cover change and their multiple impacts on natural capital in Tanzania

1 Scenarios of land use and land cover change and their multiple impacts on natural

2 capital in Tanzania

3 CLAUDIA CAPITANI1, ARNOUT VAN SOESBERGEN2,3, KUSAGA MUKAMA4,

4 ISAAC MALUGU4, BONIFACE MBILINYI5, NURDIN CHAMUYA6, BAS KEMPEN7,

5 ROGERS MALIMBWI8, REBECCA MANT2, PANTELEO MUNISHI9, MARCO

6 ANDREW NJANA10, ANTONIA ORTMANN11, PHIL PLATTS12, LISEN

7 RUNSTEN2, MARIEKE SASSEN2, PHILIPPINA SAYO4, DEO SHIRIMA13,

8 ELIKAMU ZAHABU14, NEIL D. BURGESS2,15, ROB MARCHANT1

9

10 1 York Institute for Tropical Ecosystems, University of York, Environment,

11 Heslington, York, North Yorkshire, UK. Corresponding author contact:

12 claudia.capitani@york.ac.uk

13 2 UN Environment World Conservation Monitoring Centre, Cambridge,

14 Cambridgeshire, UK

15 3 King's College London, London, London, UK

16 4 WWF Tanzania Country, Forest Program, Dar es Salaam, TZ

17 5 Sokoine University of Agriculture, Department of Agricultural Engineering and Land

18 Planning, Morogoro, TZ

19 6 Ministry of Natural Resources and Tourism, Forest and Beekeeping Division, Dar

20 es Salaam, Dar es Salaam, TZ

21 7 ISRIC World Soil Information, Wageningen, Gelderland, NL

22 8 Sokoine University of Agriculture, Department of Forest mensuration and

23 Management, Morogoro, Morogoro, TZ

24 9 Sokoine University of Agriculture, Forest Biology, Morogoro, Morogoro,TZ

25 10 Sokoine University of Agriculture, National Carbon Monitoring Centre (NCMC),

Morogoro, Morogoro, TZ

11 Food and Agriculture Organization of the United Nations Uganda Office

Kampala, Kampala, UG

12 University of York, Department of Biology, Heslington, York, UK

13 Sokoine University of Agriculture, Department of Ecosystems and Conservation,

Morogoro, Morogoro, TZ

14 Sokoine University of Agriculture, Faculty of Forestry and Nature Conservation

Morogoro, Morogoro, TZ

15 University of Copenhagen, Center for Macroecology, Evolution and Climate, The

Natural History Museum, Copenhagen, DK

51 SUMMARY

52 REDD+ (reducing emissions from deforestation, and forest degradation, plus the

53 conservation of forest carbon stocks, sustainable management of forests, and

54 enhancement of forest carbon stocks, in developing countries) requires information

55 on land use and land cover changes (LULCC) and carbon emissions trends from the

56 past to the present and into the future. Here we use the results of participatory

57 scenario development in Tanzania, to assess the potential interacting impacts on

58 carbon stock, biodiversity and water yield of alternative scenarios where REDD+ is

59 effectively implemented or not by 2025, the green economy (GE) and the business

60 as usual (BAU) respectively. Under the BAU scenario, land use and land cover

61 changes causes 296 MtC national stock loss by 2025, reduces the extent of suitable

62 habitats for endemic and rare species, mainly in encroached protected mountain

63 forests, and produce changes of water yields. In the GE scenario, national stock loss

64 decreases to 133 MtC. In this scenario, consistent LULCC impacts occur within small

65 forest patches with high carbon density, water catchment capacity and biodiversity

66 richness. Opportunities for maximising carbon emissions reductions nationally are

67 largely related to sustainable woodland management but also contain trade-offs with

68 biodiversity conservation and changes in water availability.

69

70

71

72

73

74

75

76   INTRODUCTION

77   Many countries across the tropics face major challenges around meeting the needs

78   of rapid developing and growing populations, maintaining viable ecosystem services

79   while tackling the impacts of climate change through mitigation and adaptation

80   strategies. The REDD+ mechanism has been proposed as a climate change

81   mitigation framework with the potential for reducing greenhouse gas emissions while

82   addressing rural poverty and conserving forest biodiversity and ecosystem services

83   in the 2010 16th Conference of the Parties (COP 16) of the United Nations

84   Framework Convention on Climate Change (UNFCCC). The international

85   discussions on REDD+ evolved and diversified over time (Angelsen *et al.* 2012;

86   Pistorius 2012; Lund *et al.* 2016), delivering hope, discouragement, support and

87   criticism on its feasibility and capacity to provide win-win solutions to climate change

88   mitigation - while also contributing to livelihoods, sustainable development,

89   enhanced governance, and biodiversity conservation (Sunderlin *et al.* 2014;

90   Pasgaard *et al.* 2016; Turnhout *et al.* 2016; Loft *et al.* 2017).

91   Tanzania started its REDD+ readiness process in 2008 (Burgess *et al.* 2010; URT

92   2010). The readiness process set the foundations and tested the carbon emissions

93   monitoring, reporting and evaluation system (MNRT 2015). Tanzania also recently

94   submitted its Intended Nationally Determined Contributions to UNFCCC (URT 2015);

95   these give REDD+ related actions a central national role in both mitigation and

96   adaptation contributions to climate change and development of a low emission

97   growth pathway. More recently the country has submitted its Forest Reference

98   Emission Level (FREL) to UNFCCC, currently undergoing technical assessment,

99   which estimates annual deforestation rate at 580,000 ha year^{-1} over the 2002-2013

100 period (URT 2017). Several factors drive deforestation either directly (e.g. demand

101 for farmland and biomass energy) or indirectly (e.g. high population growth rate,

102 governance weakness and unsecure land tenure (Burgess et al. 2010, Kweka et al.

103 2015).

104 The Norwegian government funded a series of REDD+ pilot projects in Tanzania,

105 which mainly focused on the local implementation of REDD+, in isolation from other

106 policy mechanisms (Blomley *et al.* 2015). Although useful, these local insights are of

107 limited use for scaling to the national context, or for creating long-term future

108 sustainable development strategies (Abidoye *et al.* 2015). A key part of the REDD+

109 mechanism in Tanzania is to estimate trade-offs between carbon emission reduction

110 and multiple co-benefits potentially achievable under REDD+, such as food and

111 energy provisions, water availability and biodiversity conservation in relation to

112 national development strategies (e.g. Tanzania Development Vision 2025, URT

113 2005). An initial assessment of potential REDD+ co-benefits in Tanzania (Miles *et al.*

114 2009; Runsten *et al.* 2013) has been followed by efforts to produce increasingly

115 specific and nation-based datasets, analyses (Augustino *et al.* 2014), scenarios

116 method (Capitani *et al.* 2016) and REDD+ Social and Environmental Safeguard

117 Standards (VPO 2013a). In this study, we present a quantitative evaluation of the

118 potential interacting impacts of two alternative socio-economic and land use and land

119 cover changes scenarios (LULCC) on carbon stock and two non-carbon forest

120 ecosystem services, biodiversity and water regulation. We analyse the spatial

121 distribution of potential win-win or conflicting outcomes from the two scenarios. Then,

122 we discuss the potential contribution of scenario analysis to the Forest Reference

123 Emission level reporting, and for identifying potential sinergies or conversely

124 preventing unintended impacts, within the framework of the Tanzania national

125 climate change and development strategies and International pledges.

126

127 METHODS

128 Our study focused on the mainland of the United Republic of Tanzania, the largest

129 country in East Africa with a population of 44.9 million people (NBS & OGCS 2013).

130 Forests cover ca. 48.1 million hectares (Mha), corresponding to 55% of Tanzania

131 mainland (National Forest Resources Monitoring and Assessment, NAFORMA,

132 MNRT 2015). This figure is higher than estimates obtained from satellite data (38.3%

133 in 2010, MNRT 2013). In Tanzania forests are managed either in protected areas-

134 various designations comprising about half of the woody volume where forest

135 management ranges from total protection (e.g. nature reserves) to regulated

136 harvesting (e.g. forest reserves), or in 'village' and 'general land' (15.4 Mha, MNRT

137 2015). An estimated 4 Mha falls under community forest management regimes under

138 Participatory Forest Management (PFM, MNRT 2008).

139

140 Scenarios development

141 We developed land use and land cover changes scenarios for Tanzania to 2025

142 following four-steps within a mixed participatory and modelling scenario framework

143 (Supplementary 1.1) that engaged 240 stakeholders from civil society and authorities

144 at local, regional and national level (WWF 2015, Capitani *et al.* 2016). First we

145 broadly defined two alternative scenarios: the business as usual (BAU)- policies

146 framework, demand for commodities, and implementation of REDD+ follow the

147 current development trajectory, and the green economy (GE)- a shift toward

148 sustainable practices is envisaged for agriculture, forestry and energy sectors

149 supported by governance enforcement, effective REDD+ implementation, and

150 enhanced productivity. Then, regional stakeholders developed locally tailored,

151 qualitative and semi-quantitative scenarios trajectories, associated with specific

152 spatial patterns and likelihood of LULCC. Next, LULCC scenarios were modelled by

153 allocating demand for cultivated land and wood biomass according to LULCC

154 likelihood spatial layers (Table S1), as expected by stakeholders and validated with

155 secondary data. By using the national land use and land cover map for 2010 (MNRT

156 2013, Fig. S1a) as baseline and the World Database on Protected Areas (IUCN &

157 UNEP-WCMC 01/2015), changes were modelled from specific land use and land

158 cover classes to arable land (cultivation expansion), to mixed cultivated-wooded land

159 (shifting cultivation), and to classes having lower tree cover and biomass without

160 cultivation replacement (degradation, e.g. from closed woodland to bushland).

161 Preliminary results were validated in a national level workshop in 2015 and refined

162 thereafter to create the results presented here. The spatial resolution of scenario

163 outputs was ca. 100 m. To maintain the local representativeness of change

164 pressures in the national scale impacts assessment on carbon and non-carbon

165 benefits, we applied a double resampling process that has reduced the accuracy of

166 our analysis (see Discussion and Supplementary 1.2).

167

168 Carbon stock

169 Biomass carbon stock was estimated for the Tanzania mainland using a national

170 dataset for above ground biomass (AGB, Ortmann 2014) based on NAFORMA forest

171 inventory data, and from land-cover-specific ratios for below ground biomass (MNRT

172 2015), litter and deadwood biomass (Willcock *et al.* 2012). The wood dry matter

173 biomass was converted to carbon by applying a 0.47 conversion factor, following the

174 national protocol (URT 2017). Top soil organic carbon content for the 0-30cm layer

175 was estimated by multiplying carbon concentration data from a national map

176 (Kempen *et al.* 2014) by the corresponding volume and bulk density obtained from

177 the Soil and Terrain Database (SOTER) of Southern Africa (Dijkshoorn 2003). Both

178 scenarios and the associated LULCC change imply C stock losses by 2025, though

179 lower in the GE than in the BAU scenario (Capitani *et al.* 2016), reflecting the need

180 of ensuring food and energy security, while allowing infrastructure development. For

181 LULCC driven carbon stock changes estimate, the baseline (Fig. S2a) was created

182 from biomass and top soil carbon datasets resampled from the original ca. 250-m

183 resolution to ca. 100-m resolution by using the nearest neighbour method. We

184 assumed that cultivation expansion depletes the five carbon pools, while shifting

185 cultivation and degradation deplete the above ground and dead wood biomass only.

186 For newly created cultivated land or shifting cultivation, carbon stocks in the

187 scenarios were estimated as the average stock of the respective classes for the

188 baseline. Carbon stock for degraded areas in the scenarios was estimated by

189 decreasing the baseline biomass proportionally to the average biomass loss for the

190 specific LULCC types expected in each pixel. Carbon stock changes were calculated

191 as the pixel base difference between the baseline and the scenarios. The final

192 results were then aggregated at 1-km resolution.

193

194 Biodiversity

195 We assessed the potential impacts of LULCC on biodiversity under the two

196 scenarios focusing on terrestrial vertebrate species as derived from the IUCN Red

197 List database (mammals, birds, amphibians and reptiles, IUCN, 2016 and BirdLife

198 International & NatureServe 2015). Species sensitive to the modelled LULCC (hence

199 LULCC-sensitive species) were selected following the IUCN classification of threats

200 from cultivation expansion (threat class 2.1, 2.2.1), livestock rearing (class 2.3),

201 wood harvesting for energy and timber (class 5.3), fire (class 7.1), and urbanization

202 (class 1) (see Salafsky *et al.* 2008). For every species, extent of occurrences (EOO)

203 layers in Tanzania were clipped to the occupied habitats by matching the associated

204 IUCN habitat classes with global cover land use types (Foden *et al.* 2013) and then

205 with our reference land use and land cover classes to generate Extent of Suitable

206 Habitat (ESH) polygons. We collected spatial distribution data and generated ESHs

207 for 164 amphibians, 311 mammals, 58 reptiles, 1002 birds species on the Tanzanian

208 mainland. Out of these 1535 terrestrial vertebrates, 177 are either classified by IUCN

209 (2016) as endemic (127) or included in the IUCN categories 'Critically Endangered,

210 Endangered and Vulnerable' (hence threatened species, 140) or both (90). We

211 calculated ESH reduction in the two scenarios for LULCC-sensitive species, focusing

212 on endemic species and threatened species with at least 1% of their range included

213 on the Tanzania mainland. We calculated a spatially explicit biodiversity index

214 prioritising species richness and rarity (BRRI, modified from van Soesbergen *et al.*

215 2016, Fig. S2b,) across Tanzania at 1-km resolution, by summing over all occurring

216 species in each grid-cell (richness) the ESH weighted by the species distribution

217 range size in Tanzania and over the globe (rarity, see Supplementary 1.3 for

218 equations).

219

220 Water yield

221 To assess the impacts of LULCC under the two scenarios on water yields we used

222 the WaterWorld V2 (Mulligan 2013) model at a resolution of 1 km. WaterWorld is a

223 fully distributed, process-based hydrological model that utilises remotely sensed and

224 globally available datasets. Baseline climate data is based on a long term

225 climatology from WorldClim (Hijmans *et al.* 2005). Land use and land cover in the

226 model is represented by fractional values for three functional vegetation types (tree,

227 herb and bare). We calculated these fractional values for each land use class in the

228 baseline and scenarios using the nearest mean fractional value for a group of cells of

229 that class for MODIS VCF data for the year 2010 (DiMicelli *et al.* 2011) thus retaining

230 variability within land use classes as well as within country. Calculations were made

231 at the ca. 100-m scenario resolution by resampling the MODIS VCF data. Final

232 baseline and scenario fractional vegetation maps were then aggregated to 1-km

233 resolution and used to run the model. Changes in water yields under each scenario

234 were analysed as changes in pixel based water balance in mm year^{-1} between the

235 baseline (Fig. S2c) and the scenarios.

236

237 Multi-dimensions scenarios assessment

238 We assessed spatial patterns of synergies and trade-offs between carbon stock,

239 biodiversity and water yield changes in the two scenarios. We focused on LULCC

240 subjected areas, though we acknowledge that impacts could also be reflected

241 outside, particularly for water. Changes in the three dimensions compared to the

242 baseline were standardised, based on the scenarios and baseline statistical

243 distribution of each dimension, and merged into a composite Red-Green-Blue (RGB)

244 plot. We defined as increasing impacts between the scenarios and the baseline the

245 decline of C stock, of BRRI index, and either positive or negative changes in water

246 yield diverging from 0. Here, we report and discuss trade-offs across scenarios by

247 comparing high to low impacts on the three dimensions.

248

249 RESULTS

250 In the BAU scenario, cultivated land is expected to expand by 5.4 Mha (0.36 Mha

251 year^{-1}) by 2025 (Fig. S1b). In addition, shifting cultivation expands over 3.5 Mha

252 (0.23 Mha year^{-1}) and degradation over 3.4 Mha (0.22 Mha year^{-1}) by 2025. In the

253 BAU scenario, 11% of LULCC occur within protected areas, mainly in state managed

254 forest reserves. In the GE scenario (Fig. S1c), cultivation expansion is reduced to 4.5

255 Mha (0.3 Mha year^{-1}) and degradation occurs over 3.6 Mha (0.23 Mha year^{-1}).

256

257 Carbon

258 In the BAU scenario, the envisaged land cover changes are estimated to result in ca.

259 296 million tonnes of carbon (MtC) national stock loss by 2025 compared to 2010.

260 The countrywide estimated carbon stock loss in the GE scenario is ca. 133 MtC by

261 2025 (Fig. 1). In the GE scenario, 37 MtC avoided emissions within protected areas

262 accounts for 23% of the emissions difference compared to the BAU scenarios.

263 Countrywide the C stock changes mostly occur within open woodland in both

264 scenarios, ranging between 58% (GE) and 65% (BAU) of total change (Table 1).

265 Under the GE scenario, following forest protection and sustainable management

266 enforcement LULCC are partially displaced to habitats with lower management

267 safeguards, such as bushland, grassland and mangrove forests.

268

269 Biodiversity

270 In the BAU scenario 326 LULCC-sensitive species are impacted by habitat

271 conversion; this includes 100 Tanzania endemic and 120 threatened species. In the

272 BAU scenario the extent of suitable habitat (ESH) reduction averages 20% for the

273 endemic species and 6.5 % for the 37 non-endemic threatened species. Under BAU

274 six species (*Arthroleptis kutogundua*, *Afrixalus morerei*, *Churamiti maridadi*,

275 *Galagoides rondoensis*, *Nectophrynoides laticeps* and *Nectophrynoides paulae*) lose

11

276 50% or more of their ESH. In the GE scenario, 317 LULCC-sensitive species are

277 impacted by LULCC. The mean ESH reduction decreases to 4% for the 91 impacted

278 endemic species and to less than 1% for the 36 non-endemic threatened species.

279 The biodiversity richness and rarity index (BRRI) is highly variable across Tanzania,

280 with the highest values mainly concentrated within the Eastern Arc Mountains (EAM)

281 biodiversity hotspot (Meng *et al.* 2016, Fig. S2b). In both scenarios (Fig. 2), the

282 highest potential impact in high BRRI areas occurs in mountain forest patches.

283 Compared to the Ge scenario, in the BAU scenario BRRI losses were locally higher,

284 due to larger habitat losses of LULCC-sensitive species, but the BRRI gains were

285 slightly wider, due to generalist species expansion in habitats with reduced canopy

286 compared to the baseline. In the GE scenario, BRRI losses extended in species-rich

287 regions not exposed to LULCC in the BAU scenario.

288

289 Water yield

290 Changes in water yields, expressed as changes in water balance, are greater under

291 the BAU scenario than the GE scenario, with a mean increase in water balance of

292 3.9 mm year^{-1} (+2%) versus 1.9 mm year^{-1} (+1%), across BAU and GE scenario

293 respectively (Fig. 3). Under the BAU scenario, nearly 10% of the country sees a

294 change in water balance of more than 50%, while under the GE scenario this is

295 6.2%. In both scenarios mountain and lowland forest and closed woodland face the

296 most intensive changes in water balance (per hectare), but woodland and wetlands

297 contribute the largest observed absolute change at national scale because they

298 cover a much bigger area than forests. Increases in water yield are generally the

299 result of land degradation, reducing the amount of water use by vegetation and thus

300 increasing available water for runoff, more closely following the rainfall pattern. In

301 addition to water use by vegetation, trees can also play an important role in

302 'capturing' occult precipitation within cloud forests (Bruijnzeel *et al.* 2011) and

303 favouring precipitation infiltration within miombo (Kashaigili & Majaliwa 2013). In the

304 baseline this contributes up to 17% of the water balance in montane forested areas

305 of the Eastern Arc, the northern volcanoes, and in the west near lake Tanganyika.

306 Forest degradation in those areas therefore is more likely to result in a reduction in

307 available water.

308

309 Multi-dimensions scenarios assessment

310 The simultaneous assessments of impacts of LULCC on carbon, biodiversity and

311 water yield gives a complex pattern for both scenarios. Few land use patches show

312 matching degrees of impact (e.g. either low or high impact in every variable); while in

313 most areas LULCC generate different combinations of impact intensity (Fig. 4). In the

314 BAU scenario, simultaneous high impacts in every dimension are mainly focused in

315 protected forests and woodlands across EAM and south-western Tanzania (Fig. 4).

316 In the GE scenario, 40% of LULCC are avoided, and simultaneous high impacts on

317 carbon, biodiversity and water yield decrease. Increased impact on carbon,

318 biodiversity and water yield is more frequent outside managed areas. In the GE

319 scenario, about 19% of LULCC occur in different areas than in the BAU scenario

320 (potential displacement). In about one-third of displaced LULCC areas, low impact

321 on carbon is associated with high impact on either biodiversity or water yield.

322

323 DISCUSSION

324 Studies that assess potential future trade-offs and interactions between carbon and

325 non-carbon benefits of natural habitat conservation are rare for East Africa (e.g. van

326 Soesbergen *et al.* 2016). Synergies and trade-offs between ecosystem services, as

327 their provision and demand change (Locatelli *et al.* 2013), with simultaneous

328 assessment of carbon and non-carbon benefits at large scale being highly

329 challenging (Busch & Grantham 2013).

330 In the highly diverse landscape of Tanzania, under land change scenarios spatial

331 patterns of impacts on carbon storage, biodiversity and water yield are not

332 homogeneous. Consistent patterns are identifiable to some extent in relation to the

333 different habitats and forest management regimes. In montane and lowland forests

334 LULCC driven impacts are usually consistent and result in high carbon stock loss,

335 biodiversity loss and water yield change. This increased water availability could

336 benefit farmers locally, but could cause severe impacts downstream (e.g. Enfors &

337 Gordon 2007; Kashaigili & Majaliwa 2013). In species-rich dry woodlands of north-

338 eastern Tanzania LULCC impact is higher on biodiversity than on carbon stock. In

339 addition, cultivated land expansion result in relatively low rates of carbon stock loss

340 per unit area but are locally associated with cumulated water deficit, and increased

341 irrigation demand. Site-specific trade-offs between carbon and non-carbon benefits

342 impacts require joined up action by decision-makers, for example management

343 interventions that link water provision with carbon storage.

344

345 Lessons for REDD+ implementation

346 The Tanzania National REDD+ Strategy (VPO 2013b) identifies three broad

347 categories of REDD+ implementation actions: improved management and

348 restoration of protection and production forest reserves, community-based forest

349 management (including non-reserved areas), and plantation forestry. Our findings

350 suggest that strictly protected forests conserve carbon, preserve biodiversity and

351 maintain the water catchment, albeit over relatively small areas. Sustainable

352 management of productive forests can support carbon emission reduction in the GE

353 scenario, but with trade-offs for biodiversity and water yield. Maximising the potential

354 benefits depends on the simultaneous enforcement of management and adequate

355 resolution of conflicts, while ensuring current and future human communities' needs

356 are met (Persha & Meshack 2015). Critical to REDD+ implementation is the risk of

357 avoiding deforestation leakage (Pfeifer *et al.* 2012). In the GE scenario, LULCC

358 impacts on biodiversity shift from rare forest species to species-rich communities in

359 semi-open habitats that have lower carbon value and hence of slightly lower priority

360 in Tanzania REDD+ framework. This suggests that ambitious REDD+ targets are

361 needed for carbon emission and habitat conversion reduction to meet biodiversity

362 conservation objectives in Tanzania.

363 Protected areas and community-based forest management areas alone are not

364 sufficient to achieve emission reductions required to fulfil the Tanzanian national

365 commitment (URT 2015), meanwhile ensuring food, water and energy security to the

366 increasing population. At the national scale in both scenarios most carbon stock

367 changes, as well as water yield and biodiversity disturbance, are anticipated in

368 general land, particularly focused along the commercial development corridors (e.g.

369 SAGCOT and Tanga). Addressing land and natural resource degradation outside

370 managed areas requires better integration of a landscape-centred REDD+ (Turnhout

371 *et al.* 2016), development (e.g. poverty reduction, food security and education) and

372 conservation policies based on broader consensus and engagement by a wide range

373 of actors that have political will and support from Government ministries, NGOs and

374 community based organisations.

375 The Forest Reference Emission Level (FREL) assessment for Tanzania estimated

376 ca. 58 $MtCO_2$ year^{-1} emitted due to deforestation (URT 2017), comparable to ca. 61

377 MtCO2 year^{-1} estimated in the BAU scenario using the same deforestation definition,

378 though a different methodology. Our demand driven LULCC scenarios provide a

379 useful estimate on the magnitude of deforestation fraction not detectable from

380 satellite images (Hojas-Gascon *et al.* 2015). The multi-dimensional quantitative

381 assessment can contribute to ongoing national and international debates

382 surrounding expectations for carbon and co-benefits values; these can be used to

383 chart the triple wins or compounded losses of potential futures. The scenarios, and

384 importantly the wider information behind these, can be used to support current

385 negotiations of desirable or undesirable impacts across diverse beneficiaries of

386 forest services, in relation to REDD+, the Intergovernmental Platform on Biodiversity

387 and Ecosystem Services and the Sustainable Development Goals.

388

389 Caveats and limitations

390 As with all results from scenario analysis, our findings have inherent uncertainty. The

391 presented results are not predictions but depict potential impacts within the range of

392 our scenario trajectories. To maximise relevance and legitimacy, to represent

393 multiple scale perspectives, interaction of key components of water, carbon and

394 biodiversity, and to overcome consistent challenges of time series data quality and

395 scarcity for Tanzania, we put great efforts in model and datasets customization.

396 However, the uncertainties generated by this approach should be considered when

397 drawing conclusions from the presented results.

398 Dataset resampling has affected the accuracy of impacts spatial patterns and of the

399 multi-dimension assessment at pixel level. The choice of indices also influenced the

400 presented findings. For example, the adopted biodiversity index has the advantage

401   of being sensitive to LULCC. However, it does not consider other essential aspects

402   of biodiversity (Supplementary 1.3) or interactions with other sources of disturbance

403   (e.g. climate change disturbance (Foden et al. 2013). Prioritization of biodiversity and

404   ecosystem services conservation should account for internal feedbacks

405   characterised by connectivity and complementarity (Kukkala and Moilanen 2017),

406   which are not captured by pixel-based analysis.

407   The selected thematic and temporal scopes influence our findings. Considering

408   additional dimensions (e.g. social) and different impacts thresholds (e.g. negotiated

409   amongst stakeholders) could change the outcomes of multiple co-benefits

410   assessment. The limited scenarios temporal horizon was set to comply with tangible

411   objectives such as the Tanzania Development Vision 2025 (URT 2005) and the

412   REDD+ roadmap, but this could limit the scope for green development assessment.

413   In respect to the relevance for supporting decision making, we successfully engaged

414   with a broad range of stakeholders from across the country to co-produce scenarios,

415   build local assessment capacity and consensus around the scenarios outputs. Such

416   approaches need integrating into institutional frameworks to effectively influence

417   policy formulation and implementation to mainstream biodiversity conservation and

418   ecosystem services provision in future land use planning.

419

420   Supplementary material

421   For supplementary material accompanying this paper, visit

422   www.cambridge.org/core/journals/environmental-conservation

423   Acknowledgements

424   We thank the 180 stakeholders engaged in the scenarios development across

425   Tanzania regions and 60 nationally focused decision-makers and delegates of the

426 NGO community in Tanzania who provided validation and feedback at the national

427 synthesis workshop. We especially thank staff within the WWF Tanzania office.

428 Financial support

429 This work was funded by the Norwegian Government International Climate and

430 Forest Initiative through their Royal Embassy, and the Ministry for Foreign Affairs of

431 Finland, the University of York and the UNEP-WCMC.

432

433 REFERENCES

434 Abidoye B, Mungatana E, Mahlalela L, Sacolo T, Babalola F. (2015) Forest

435 ecosystems in the transition to a green economy and the role of REDD + in the

436 United Republic of Tanzania. UNEP 2015. eds. I Mulder, B Mbote, Nairobi, Kenya.

437 Angelsen A, Brockhaus M, Sunderlin WD, Verchot LV (2012) Analysing REDD +.

438 Challenges and choices. eds. A Angelsen, M Brockhaus, WD Sunderlin, LV Verchot.

439 Bogor, Indonesia.

440 Augustino S, Bowles P, Carr J, Cox N, Hicks C, Mant R, Mbilinyi B, Meng H,

441 Ravilious C, Runsten L, Salvaterra T, Dos Santos S, Tognelli MF, Zahabu E (2014).

442 Environmental and social spatial data to support REDD+ safeguards and planning in

443 Tanzania. SUA, Morogoro, URT; UNEP-WCMC, Cambridge, UK; IUCN Global

444 Species Programme, Cambridge UK and Washington DC, USA.

445 BirdLife International, NatureServe (2015) Bird species distribution maps of the

446 world. BirdLife International, Cambridge, UK and NatureServe, Arlington, USA.

447 Blomley T, Edwards K, Kingazi S, Lukumbuzya K, Vesa L (2015) REDD + hits the

448 ground REDD + hits the ground. ed. J Mayers. London, UK.

449 Bruijnzeel LA, Mulligan M, Scatena FN (2011) Hydrometeorology of tropical montane

450 cloud forests: emerging patterns. *Hydrological Processes* **25**: 465-498.

451   Burgess ND, Bahane B, Clairs T, Danielsen F, Dalsgaard S, Funder M, Hagelberg N,

452   Harrison P, Haule C, Kabalimu K, Kilahama F, Kilawe E, Lewis SL, Lovett JC, Lyatuu

453   G, Marshall AR, Meshack C, Miles L, Milledge SAH, Munishi PKT, *et al.* (2010)

454   Getting ready for REDD+ in Tanzania: a case study of progress and challenges.

455   *Oryx* **44**: 339–351.

456   Busch J, Grantham HS (2013) Parks versus payments: reconciling divergent policy

457   responses to biodiversity loss and climate change from tropical deforestation.

458   *Environmental Research Letters* **8**: 34028.

459   Capitani C, Mukama K, Mbilinyi B, Malugu IO, Munishi PKT, Burgess ND, Platts PJ,

460   Sallu SM, Marchant R (2016) From Local Scenarios to National Maps: A

461   Participatory Framework for Envisioning the Future of Tanzania. *Ecology and*

462   *Society* **21**: 4.

463   Dijkshoorn JA (2003) SOTER database for Southern Africa. ISRIC – World Soil

464   Information, Wageningen, NL.

465   DiMicelli CM, Carroll ML, Sohlberg RA, Huang C, Hansen MC, Townshend JRG

466   (2011) Annual global automated MODIS vegetation continuous fields (mod44b) at

467   250 m spatial resolution for data years beginning day 65, 2000 - 2010, collection 5

468   percent tree cover. University of Maryland, College Park, MD, USA.

469   Enfors E I, Gordon LJ (2007) Analysing resilience in dryland agro-ecosystems: a

470   case study of the Makanya catchment in Tanzania over the past 50 years. *Land*

471   *degradation and development* **18**: 680-696.

472   Foden WB, Butchart SHM, Stuart SN, Vié J-C, Akçakaya HR, Angulo A, DeVantier L

473   M, Gutsche A, Turak E, Cao L, Donner SD, Katariya V, Bernard R, Holland RA,

474   Hughes AF, O'Hanlon SE, Garnett ST, Şekercioğlu ÇH, Mace GM, Hoffmann M, *et*

475   *al.* (2013) Identifying the World's Most Climate Change Vulnerable Species: A

476 Systematic Trait-Based Assessment of all Birds, Amphibians and Corals. *PLoS ONE*

477 **8**: e65427 URL

478 Hijmans RJ, Cameron SE, Parra JL, Jones PG, Jarvis A (2005) Very high resolution

479 interpolated climate surfaces for global land areas. *International Journal of*

480 *Climatology* **25**: 1965–1978.

481 Hojas-Gascon L, Cerutti PO, Eva H, Nasi R, Martius C (2015) Monitoring

482 deforestation and forest degradation in the context of REDD + Lessons from

483 Tanzania. Bogor, Indonesia: CIFOR. DOI: 10.17528/cifor/005642

484 IUCN, UNEP-WCMC. The World Database on Protected Areas (WDPA). Cambridge,

485 2015. Downloaded 01/2015. [www dataset]. URL http://www.protectedplanet.net.

486 IUCN 2016. The IUCN Red List of Threatened Species. Version 2016-3.

487 Downloaded 05/2016. [www datset]. URL http://www.iucnredlist.org.

488 Kashaigili JJ, Majaliwa AM (2013) Implications of land use and land cover changes

489 on hydrological regimes of the Malagarasi river, Tanzania. *Journal of agricultural*

490 *sciences and applications* **2**: 45-50

491 Kempen B, Kaaya A, Mhaiki CN, Kiluvia S, Ruiperez-Gonzalez M (2014) Modelling

492 and mapping the topsoil organic carbon content for Tanzania. *Geophysical Research*

493 *Abstracts* **16**: 10413.

494 Kukkala SA, Moilanen A (2017) Ecosystem services and connectivity in spatial

495 conservation prioritization. *Landscape Ecology* **32**:5–14.

496 Locatelli B, Imbach P, Wunder S (2013) Synergies and trade-offs between

497 ecosystem services in Costa Rica. *Environmental Conservation* **41**: 27–36.

498 Loft L, Pham TT, Wong GY, Brockhaus M, Le DN, Tjajadi JS, Luttrell C (2017) Risks

499 to REDD+: potential pitfalls for policy design and implementation. *Environmental*

500 *Conservation* **44**:44–55.

501 Lund JF, Sungusia E, Mabele MB, Scheba A (2016) Promising Change, Delivering

502 Continuity: REDD+ as Conservation Fad. *World Development* **89**:124-139.

503 Meng H, Carr J, Beraducci J, Bowles P, Branch W, Capitani C, Chenga J, Cox N,

504 Howell K, Malonza P, Marchant R, Mbilinyi B, Mukama K, Msuya C, Platts P, Safari

505 I, Spawls S, Shennan-Farpon Y, Wagner P, Burgess N (2016) Tanzania's reptile

506 biodiversity: Distribution, threats and climate change vulnerability. *Biological*

507 *Conservation* **4**:72-82.

508 Miles L, Kabalimu K, Bahane B, Ravilious C, Dunning E, Bertzky M, Kapos V,

509 Dickson B (2009) Carbon, Biodiversity and Ecosystem Services: Exploring Co-

510 Benefits. Tanzania. Prepared by UNEP-WCMC, Cambridge, UK, Forestry and

511 Beekeeping Division, Ministry of Natural Resources and Tourism, Dar es Salaam,

512 URT. UN-REDD Programme, URT. [www document]. URL http://www.unep-

513 wcmc.org/climate/publications.aspx.

514 Ministry of Natural Resources and Tourism (MNRT) (2008) Participatory Forest

515 Management in Tanzania: Facts and Figures. Dar es Salaam, URT.

516 Ministry of Natural Resources and Tourism (MNRT) (2013) Tanzania Mainland Land

517 Use - Land Cover. Tanzania Forest Services Agency, Dar es Salaam, URT.

518 Ministry of Natural Resources and Tourism (MNRT) (2015) National Forest

519 Resources Monitoring and Assessment of Tanzania Mainland. Dar es Salaam, URT.

520 Mulligan M (2013). WaterWorld: a self parameterising, physically based model for

521 application in data-poor but problem-rich environments. *Hydrology Research* **44**:

522 748–769.

523 National Bureau of Statistics (NBS), Office of Chief Government Statistician (OCGS),

524 Zanzibar (2013) The 2012 Population and Housing Census: Population distribution

525 by administrative area. Dar es Salaam, URT.

526 Ortmann A. (2014) Estimating land cover changes and current carbon stock in

527 Tanzania in the context of REDD+. Master thesis, Global Change Ecology Graduate

528 Program (M.Sc.) at the University of Bayreuth within the Elite Network of Bavaria,

529 DE.

530 Pasgaard M, Sun Z, Müller D, Mertz O (2016) Challenges and opportunities for

531 REDD+: A reality check from perspectives of effectiveness, efficiency and equity.

532 *Environmental Science and Policy* **63**: 161–169.

533 Persha L, Meshack C (2015) Is Tanzania's Joint Forest Management Program a

534 Triple Win? Understanding Causal Pathways for Livelihoods, Governance and

535 Forest Condition Impacts. 3ie Grantee Final Report. New Delhi: International

536 Initiative for Impact Evaluation (3ie).

537 Pfeifer M, Burgess ND, Swetnam RD, Platts PJ, Willcock S, Marchant R (2012)

538 Protected Areas: Mixed Success in Conserving East Africa's Evergreen Forests.

539 *PLoS ONE* **7**: e39337.

540 Pistorius T (2012) From RED to REDD+: The Evolution of a Forest-Based Mitigation

541 Approach for Developing Countries. *Current Opinion in Environmental Sustainability*

542 **4**: 6 638–45.

543 Runsten L, Ravilious C, Kashindye A, Giliba R, Hailakwahi V, Kashaga LRA, Khalid

544 S, Mbilinyi B, Mwampashi Y, Pastory M, Mant R, Osti M, Crête P, Pekkarinen A,

545 Leppanen M, Miles L (2013) Using Spatial Information to Support Decisions on

546 Safeguards and Multiple Benefits for REDD + in Tanzania. UNEP-WCMC,

547 Cambridge, UK. Ministry of Natural Resources and Tourism, Dar es Salaam, URT.

548 [www document]. URL http://www.un-redd.org/tabid/5954/Default.aspx

549 Salafsky N, Salzer D, Stattersfield AJ, Hilton-Taylor C, Neugarten R, Butchart SHM,

550 Collen B, Cox N, Master LL, O'Connor S, Wilkie D (2008) A Standard Lexicon for

551   Biodiversity Conservation: Unified Classifications of Threats and Actions.

552   *Conservation Biology* **22**: 897–911.

553   Sunderlin WD, Pratama CD, Bos AB, Avitabile V, Sills EO, Sassi C de, Joseph S,

554   Agustavia M, Pribadi UA, Anandadas A (2014) REDD+ on the ground: The need for

555   scientific evidence In *REDD+ on the ground: A case book of subnational initiatives*

556   *across the globe*. eds. EO Sills, SS Atmadja, C de Sassi, AE Duchelle, DL Kweka,

557   IAP Resosudarmo, WD Sunderlin, pp. 2-32. Bogor, Indonesia: CIFOR.

558   Turnhout E, Gupta A, Weatherley-Singh J, Vijge MJ, de Koning J, Visseren-

559   Hamakers IJ, Herold M, Lederer M (2016) Envisioning REDD+ in a post-Paris era:

560   between evolving expectations and current practice. *Wiley Interdisciplinary Reviews*

561   *Climate Change* 8:e425.

562   United Republic of Tanzania (URT) (2005) Tanzania Development Vision 2025.

563   Planning Commission, Dar es Salaam, URT. [WWW document]. URL

564   http://www.tzonline.org/pdf/theTanzaniadevelopmentvision.pdf

565   United Republic of Tanzania (URT) (2010) Readiness Preparation Proposal (R-PP).

566   Dar es Salaam, Tanzania. [www document]. URL

567   http://www.forestcarbonpartnership.org/sites/forestcarbonpartnership.org/files/Docu

568   ments/PDF/Jun2010/Tanzania-Revised_R-PP_main_document_V9-10.06.2010.pdf

569   United Republic of Tanzania (URT) (2015) Intended Nationally Determined

570   Contributions to the UNFCCC. Dar es Salaam, URT.

571   United Republic of Tanzania (URT) (2017) Tanzania's forest reference emission

572   level submission to the UNFCCC. Dar es Salaam, URT.

573   van Soesbergen A, Arnell AP, Sassen M, Stuch B, Schaldach R, Göpel J, Vervoort

574   J, Mason-D'Croz D, Islam S, Palazzo A (2016) Exploring future agricultural

575   development and biodiversity in Uganda, Rwanda and Burundi: a spatially explicit

576   scenario-based assessment. *Regional Environmental Change*. doi:10.1007/s10113-

577   016-0983-6

578   Vice President's Office (VPO) (2013a) The Tanzania REDD+ social and

579   environmental safeguard standards, Final Draft Dar es Salaam, URT.

580   Vice President's Office (VPO) (2013b) National strategy for reduced emissions from

581   deforestation and forest degradation (REDD+). Dar es Salaam, URT.

582   Willcock S, Phillips OL, Platts PJ, Balmford A, Burgess ND, Lovett JC, Ahrends A,

583   Bayliss J, Doggart N, Doody K, Fanning E, Green J, Hall J, Howell KL, Marchant R,

584   Marshall AR, Mbilinyi B, Munishi PKT, Owen N, Swetnam RD, *et al.* (2012) Towards

585   Regional, Error-Bounded Landscape Carbon Storage Estimates for Data-Deficient

586   Areas of the World. *PloS One* **7**: e44795.

587   World Wildlife Fund (WWF) Tanzania Country Office (2015) WWF REDD+ pilot

588   project. Final project report. WWF, Dar es Salaam, URT. [www document]. URL

589   http://d2ouvy59p0dg6k.cloudfront.net/downloads/wwf___redd__final_project_report_

590   __10th_april_2015_1.pdf.

591

592

593

594

595

596

597

598

599

600

601 FIGURE LEGENDS

602 Figure 1. Changes in total carbon stock (carbon tonnes per hectare, C t ha^{-1}) in the

603 business as usual (BAU) and green economy (GE) scenarios across Tanzania by

604 2025.

605

606 Figure 2. Changes in biodiversity richness and rarity index (BRRI) for terrestrial

607 vertebrates in the business as usual (BAU) and green economy (GE) scenarios

608 across Tanzania by 2025. Negative and positive changes relates to prevalent losses

609 and gains of species suitable habitats, respectively.

610

611 Figure 3. Changes in water yields per year (mm year^{-1}) in the business as usual

612 (BAU) and green economy (GE) scenarios across Tanzania by 2025. In both

613 scenarios yield increment (blue shades) compared to the baseline is more frequent

614 than yield decrease (red shades).

615

616 Figure 4: Red-Green-Blue (RGB) plot of combined impacts on carbon stocks (black

617 to green), biodiversity (BRRI, black to red) and water yield (black to blue) under the

618 business as usual (BAU) and green economy (GE) scenarios across Tanzania by

619 2025. Areas mapped in black indicate low impact values and light colours high

620 impact values for all three dimensions. The three-dimensional legend is represented

621 in two visions at the bottom left of the figure. The upper vision shows, for each cube

622 face, the colour combinations of the three dimensions when one is at its maximum

623 value and the other two are varying. The lower vision shows, for each cube face, the

624 colour combination of the three dimensions when one is at its lowest value and the

625 other two are varying.

626 Table 1. Share of carbon (C) stock changes (million tonnes, Mt, and percentage of

627 the total land cover class C stock, %) by different land cover classes in the business

628 as usual (BAU) and green economy (GE) scenarios. Classes are grouped according

629 to the national definition of forests, other wooded land and other land, URT 2017.

630 Carbon stock losses in the BAU scenario within protected areas (PAs) are reported

631 separately.

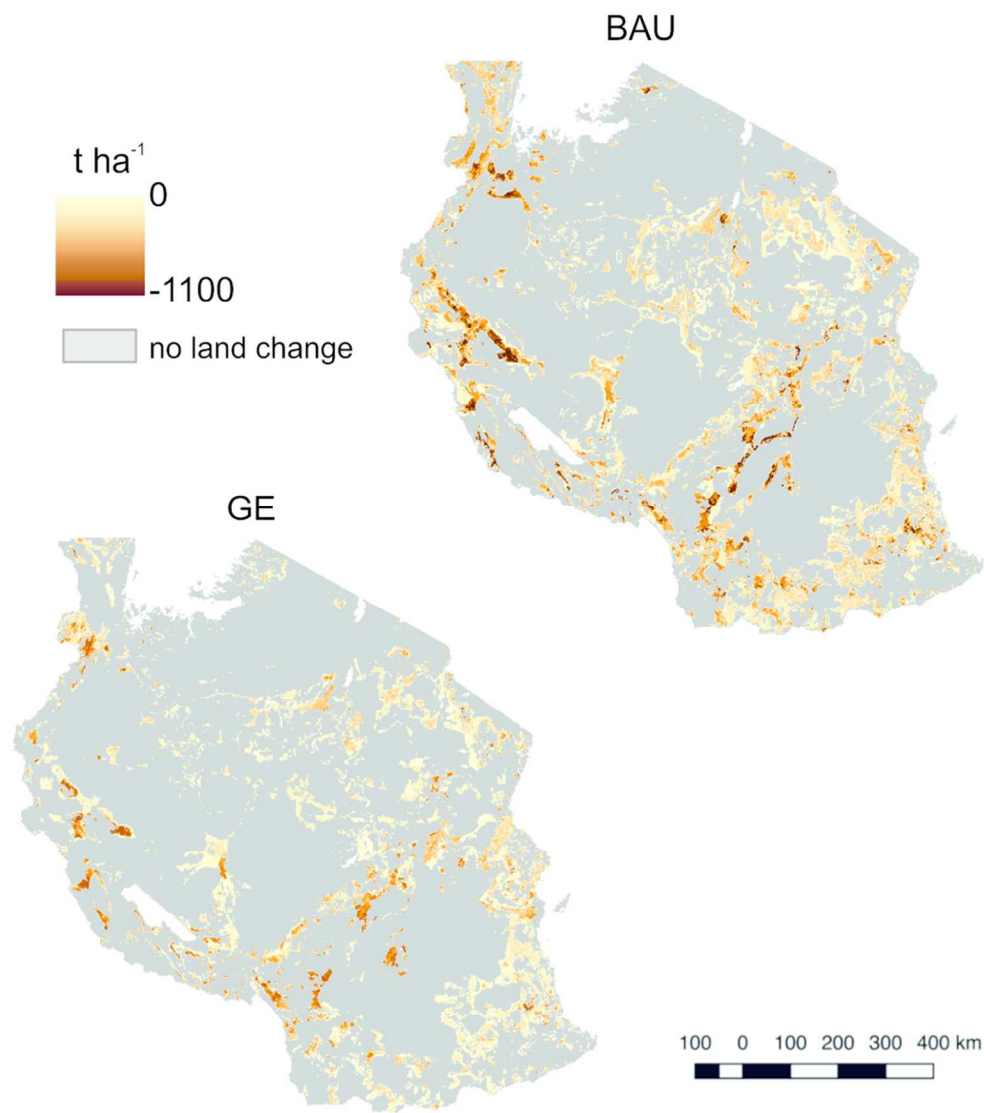|	BAU	BAU: losses within PAs	GE
	C Mt - (%)	C Mt - (%)	C Mt - (%)
Forests			
Mountain & lowland forest	6 (5)	4 (3)	<1 (<1)
Closed woodland	42 (7)	5 (1)	5 (1)
Open woodland	192 (20)	4 (2)	79 (8)
Mangrove forest	<1 (3)	<1 (<1)	<1 (5)
Thicket	3 (21)	<1 (<1)	0 (0)
Other wooded land			
Bushland	33 (9)	2 (<1)	39 (10)
Grassland	5 (3)	<1 (<1)	8 (6)
Other land			
Wetlands	15 (19)	2 (2)	5 (6)

Figure 1. Changes in total carbon stock (carbon tonnes per hectare, C t ha-1) in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025.
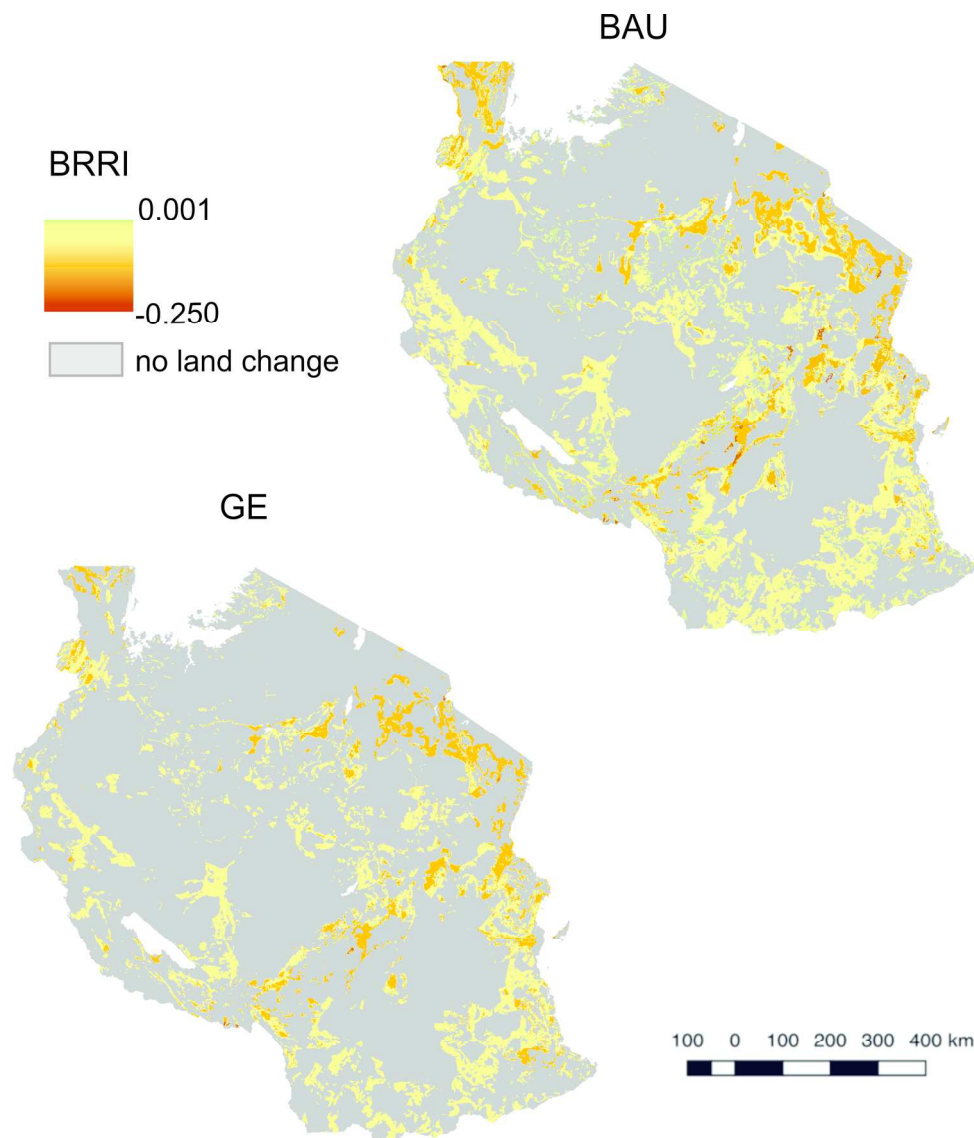
92x103mm (300 x 300 DPI)

Figure 2. Changes in biodiversity richness and rarity index (BRRI) for terrestrial vertebrates in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. Negative and positive changes relates to prevalent losses and gains of species suitable habitats, respectively.
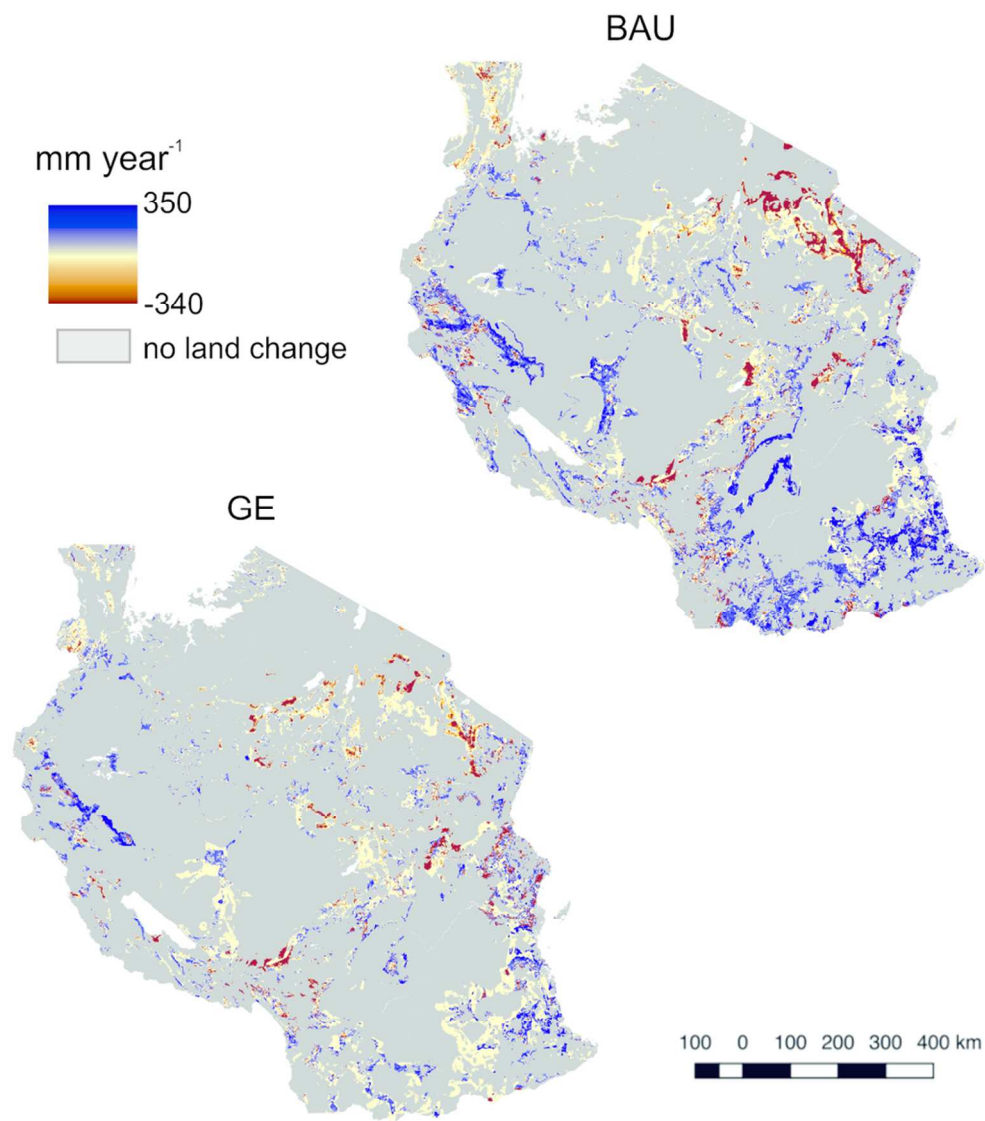
93x105mm (600 x 600 DPI)

Figure 3. Changes in water yields per year (mm year-1) in the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. In both scenarios yield increment (blue shades) compared to the baseline is more frequent than yield decrease (red shades).
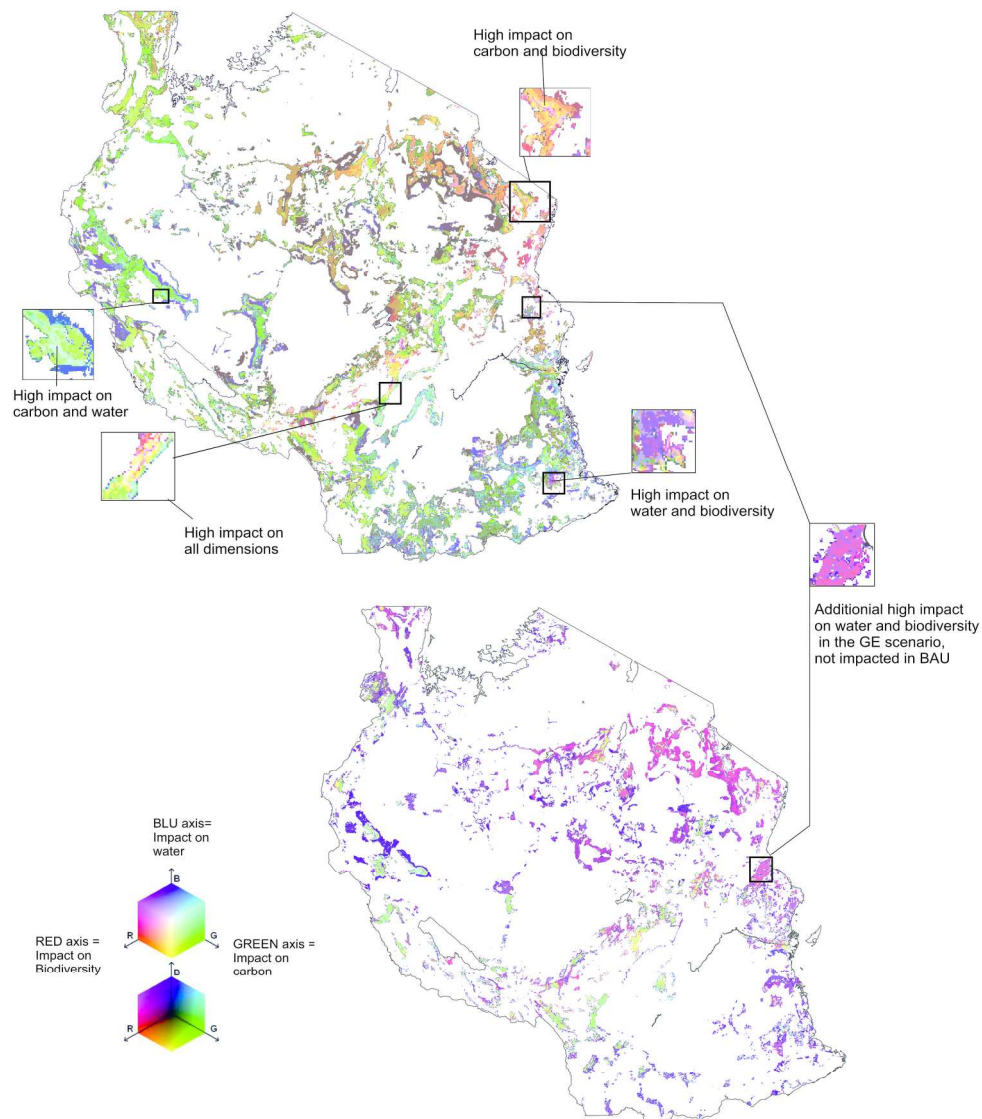
93x105mm (300 x 300 DPI)

Figure 4: Red-Green-Blue (RGB) plot of combined impacts on carbon stocks (black to green), biodiversity (BRRI, black to red) and water yield (black to blue) under the business as usual (BAU) and green economy (GE) scenarios across Tanzania by 2025. Areas mapped in black indicate low impact values and light colours high impact values for all three dimensions. The three-dimensional legend is represented in two visions at the bottom left of the figure. The upper vision shows, for each cube face, the colour combinations of the three dimensions when one is at its maximum value and the other two are varying. The lower vision shows, for each cube face, the colour combination of the three dimensions when one is at its lowest value and the other two are varying.

99x119mm (600 x 600 DPI)

Supplementary material – (.pdf 722 Kb)

This Supplementary provides details on the scenario development framework; the baseline maps for carbon and non-carbon benefits assessment, along with caveats and potential sources of error in datasets manipulation; and, the biodiversity richness and rarity index.

1.1 Scenarios development framework

Our scenario development framework aimed to tackle the challenges of translating qualitative narratives into quantitative scenarios incorporating indigenous and local knowledge. Following a mixed participatory and modelling framework (Table S1), our approach allows translation of stakeholders' developed qualitative and semi-quantitative scenarios trajectories and land use and land cover change patterns into quantitative and spatially explicit information.

Table S1. Steps of the participatory scenario development framework

Step 1 Scenarios definitions	Business as usual: policy framework, demand for commodities, and implementation of REDD+ follow the current development trajectory. Green economy: shift toward sustainable practices for agriculture, forestry and energy sectors supported by governance enforcement, effective REDD+ implementation, and enhanced productivity.
Step 2 Scenarios development by stakeholders	a) Development of qualitative and semi-quantitative socio-economic and environmental trajectories of change and relative drivers by main livelihood sectors identified at regional level by multiple stakeholders. b) Identification of specific spatial patterns of land use and land cover changes (LULCC) related to expected trajectories and drivers of change (e.g. "*high likelihood of conversion from closed woodland to*

	grassland due to charcoal production near roads and in districts where governance is weak in region X").
Step 3 Modeling	a) Quantification of demand for cultivated land and wood biomass according to secondary data[1] and expected trajectories. In this study, the business as usual scenario refers to the BAU2 quantitative scenario detailed in Capitani et al. (2016; Appendix 2). Business as usual: 30% expansion for both cultivated and mixed cultivated-wooded land; pro-capita annual wood volume demand = 0.87 m^3. Green economy: 10% increase in crop productivity no expansion of shifting cultivation; 50% reduction of wood biomass harvesting exceeding available sustainable cut. b) Spatial allocation of LULCC based on scalar composite indicators of likelihood of change calculated for different types of LULCC following the stakeholders' assessment and calculated from global and national reference datasets (corrected through locally obtained information when necessary)[1] according to the formula: $$SI_{lulcc} = (sp_1 + sp_2 + sp_3) \times m \times pas$$ SI_{lulcc}, composite indicators of likelihood of each specific LULCC; reclassified and standardized spatial datasets affecting LULCC likelihood (sp_n); m = 0/1 masking factor derived from crop suitability and slope to mask out unsuitable areas for cultivation expansion; pas, protected areas mask used to limit LULCC likelihood according to the rules: likelihood of LULCC occurring within protected areas decreasing

	with the distance from protected areas border in the BAU scenario (pas decreasing from 1 to 0); LULCC not occurring within protected areas in the GE scenario ($pas = 0$).
	Demand for land and for biomass is allocated through specific LULCC from the pixels with the highest likelihood of change until demand is fulfilled.
Step 4 Iteration	Validation of preliminary results, feedback and synthesis workshop with regional and national stakeholders; model and outputs refinement.

[1] See Appendix 2 Capitani et al. 2016.

1.2 Scenarios and baseline maps

The scenario outputs (Fig. S1) were generated with a spatial resolution of ca. 100 m, in agreement with the population density dataset (WorldPop, Tatem 2017[i]), representing one of the major driving forces of land changes in our scenarios. Impacts from land use and land cover change scenarios in Tanzania on carbon, biodiversity and water yield were calculated using datasets derived from different inputs, at different resolution and with different methods (Fig. S2).

Land use and land cover classes (MNRT 2013)
- Built-up area
- Bushland
- Closed woodland
- Cultivated bushland
- Cultivated woodland
- Forest plantation
- Fresh water; Salt water
- Grains and other crops
- Grassland
- Ice
- Mangrove forest
- Montane and lowland forest
- Open land
- Open woodland
- Thickets
- Wetland
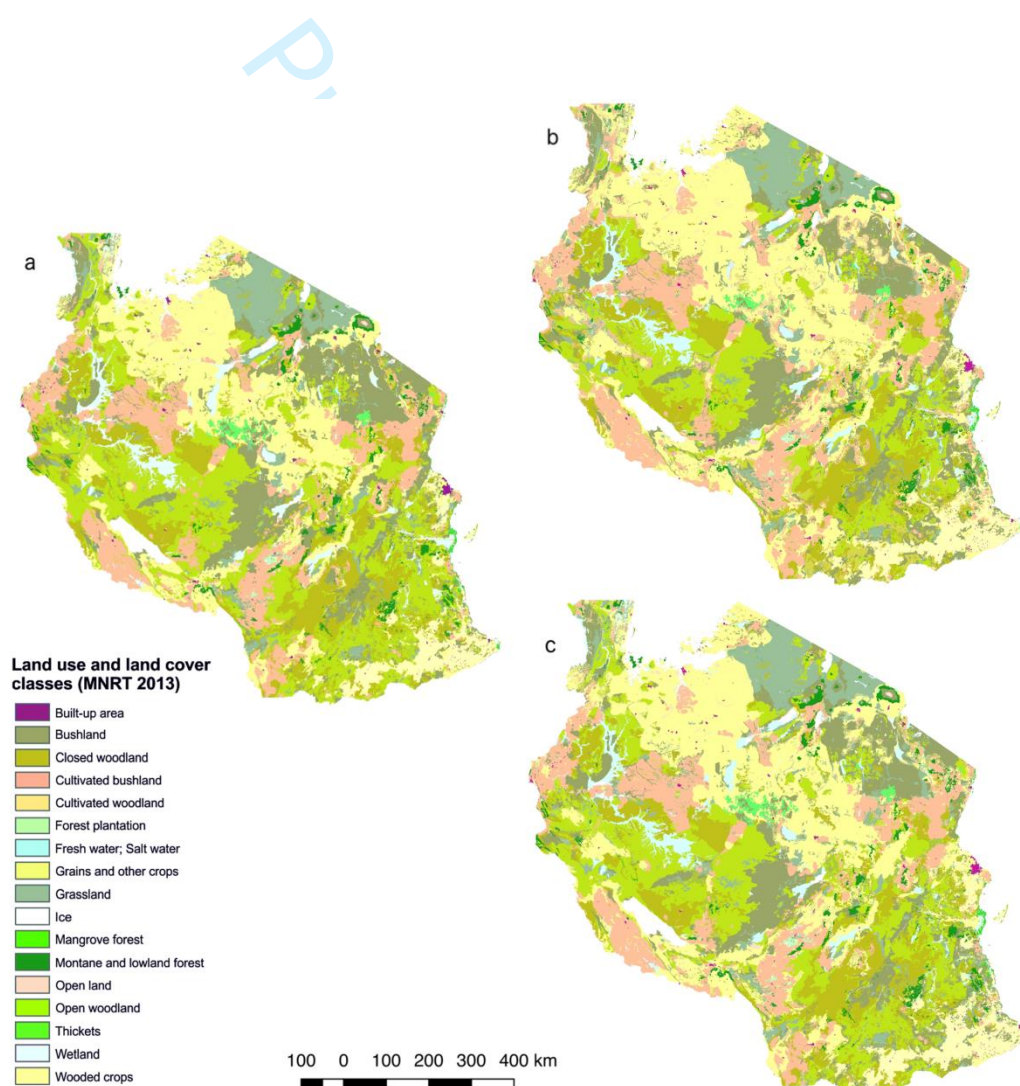- Wooded crops

100 0 100 200 300 400 km

Figure S1. Land use and land cover reference map for 2010 (a, MNRT 2013) and for b) the business as usual and c) the green economy scenarios. Scenario output maps can be obtained upon request from the authors.
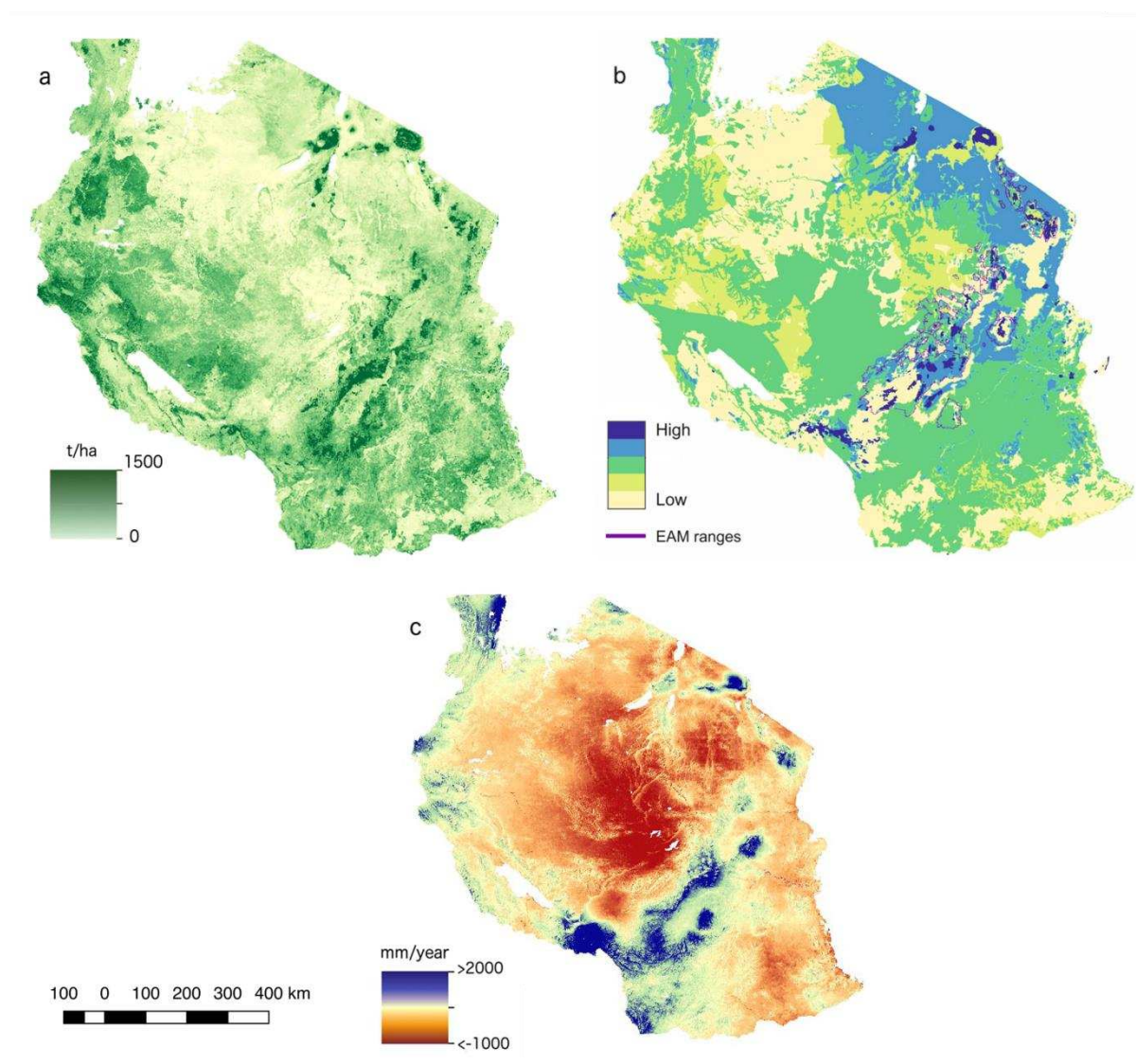
Figure S2 - Baseline maps for total carbon stock (a, ton ha^{-1}), biodiversity richness and rarity index of terrestrial vertebrates (b, range between 0 and 0.89) and water yield (c, mm year^{-1}) in Tanzania mainland. In b) the Eastern Arc Mountains biodiversity hotspot boundaries are represented by the purple line.

The high resolution adopted for the scenario analysis was helpful in incorporating local knowledge collected during the regional workshops, e.g. for simulating local patterns of small forest patches encroachment. To transfer the local representativeness of change pressures into the national scale impacts assessment

on carbon and non-carbon benefits, we altered the spatial resolution of the layers used to calculate carbon stock, biodiversity and water yield change, in order to match the ca. 100-m scenario resolution. Then we generalised the results at 1-km resolution. This double resampling process has determined a loss of accuracy in the analysis.

For biodiversity and water yield, the downscaling of the original input datasets at the scenario resolution was applied to match the reference habitat types and land cover classes with those used for the scenario analysis. Then the biodiversity and the water yield indices and their changes were calculated at 1-km resolution.

For carbon stock, the biomass and soil carbon stock layers were downscaled from ca. 250 to ca. 100 m resolution, to apply the change pressure on biomass and land determined by the specific land change expected in the scenarios (e.g. form forest to cultivated land, from closed woodland to bushland). Then changes were aggregate at 1-km resolution. The total amount of carbon biomass removed is upper limited by land and biomass demand set for the scenarios. However, the pixel-base allocation for the carbon stock change is influenced by the pixel-base carbon density, particularly for soil stock, and therefore is affected by the resampling process.

1.3 Biodiversity richness and rarity index

The Biodiversity richness and rarity index in the baseline $BRRI_{gt_0}$ was calculated for each grid-cell (g) by the formula:

$$BRRI_{gt_0} = \sum_{1}^{i}(\frac{ESH_{igt_0}}{ESH_{it_0}} \times R_i)$$

with ESH_{igt_0} the extent of suitable habitat of the i species in each pixel g, ESH_{it_0} the total extent of suitable habitat of the i species in Tanzania and R_i the ratio of the distribution range of the i species in Tanzania over the globe, at the time t_0. Changes between the scenarios and the baseline where calculated for each pixel (g)

$$BRRI_g = \sum_{1}^{i}(\frac{ESH_{igt_1} - ESH_{igt_0}}{ESH_{it_0}} \times R_i)$$

with ESH_{igt} the extent of suitable habitat of the i species in each pixel g in the scenario (t_1) or in the baseline (t_0), ESH_{it_0} the total extent of suitable habitat of the i species in Tanzania in the baseline and R_i the ratio of the distribution range of the i species.

When calculating the BRRI changes in the future scenarios we assumed that:

- LULCC-sensitive species abandon habitats converted to cultivated land or degraded;

- non-LULCC-sensitive species lose habitat due to conversion to cultivated land (e.g species mainly associated with forest or closed canopy woodland or generalist species reported not to be tolerant to agriculture activities);

- non-LULCC-sensitive species mainly found in grassland can gain habitat following degradation of woodland and bushland, when degradation is above 15m^3 ha^{-1} wood biomass loss.

These rules are based on the reported habitat preference for the species[ii], on the

reference land use and land cover classes, and on the biomass changes calculated for the scenarios; gains are considered only within the extent of occurrence of each species. We did not consider other factors than habitat that could affect species capacity of moving or adapting to changes.

The adopted biodiversity richness and rarity index (BRRI) has the advantages of being calculated from data relatively easy to obtain on a large scale, and of being directly sensitive to LULCC, compared to other quantitative indices (e.g. species abundance, richness, diversity). However, it doesn't consider multiple aspect of biodiversity complexity, e.g. functional or taxonomic diversity, connectivity, complementarity, species adaptation capacity. In Tanzania the BRRI represents well the highly endemic montane forests and species-rich woodlands, and particularly emphasized the impacts of habitat changes on rare species. Using other indices, or other prioritisation approaches, different spatial pattern would emerge, e.g. weighting all species equally as in the species richness index.

[i] Tatem, A. J. (2017) WorldPop, open data for spatial demography. Sci. Data 4:170004 doi: 10.1038/sdata.2017.4

[ii] IUCN 2016. The IUCN Red List of Threatened Species. Version 2016-3. Downloaded 05/2016. [www datset]. URL http://www.iucnredlist.org.