1 **Title:** Spatial conservation planning with ecological and economic feedback effects

2 **Abstract**

3 Most spatial conservation prioritisations being implemented across the globe are

4 based on static approaches to conservation planning. These use snapshots of

5 systems to support decision-making. However, ignoring the dynamic nature of

6 systems can result in misleading spatial prioritisations and missed opportunities to

7 encourage participation in conservation programmes. Using a modelling approach, we

8 show that integrating economic and ecological feedbacks into conservation planning

9 improved social and ecological outcomes. We developed an approach that enabled

10 accounting for feedbacks of farmland set-asides using a popular conservation

11 planning tool. We empirically assessed the impact of ignoring feedbacks on plans to

12 restore the Brazilian Atlantic Forest by comparing outcomes of our approach and a

13 widely used static approach. The proposed approach attained better conservation

14 outcomes than a static approach, at about 7% lower cost, while also allowing more

15 farmers to benefit economically from the set-aside scheme through capitalising on the

16 differences between their opportunity costs and the amount paid by the scheme.

17 Accounting for feedbacks led to substantially different areas being prioritised for

18 farmland set-asides, and to more farmers being included in the set-aside scheme.

19 These results show important benefits from understanding, and then working with,

20 feedbacks that inevitably accompany large-scale conservation interventions. Our

21 approach is the first to integrate both environmental and economic feedbacks into

22 spatial conservation planning, and model information rent capture. In doing so, it

23 demonstrates how existing economic incentives can be used to encourage farmers to

24 join a conservation set-aside, while still resulting in a lower overall intervention cost.

Introduction

Efficient allocation of conservation resources is vital, given the limited funding for conservation and rapid loss of biodiversity (Ceballos et al., 2015). Systematic conservation planning focuses on optimizing conservation outcomes cost-effectively, with thousands of systematic conservation plans developed around the globe (McIntosh et al., 2017). However, most systematic conservation plans are still based on static snapshots of the ecological and socio-economic systems to be managed (McIntosh et al., 2016).Typically, planned actions are implemented over periods of years or decades (Pressey et al., 2013), which gives opportunity for the system to react. Ignoring the dynamic nature of these systems can overlook unintended feedbacks of the conservation plan, risking undermined conservation outcomes, and even misleading recommendations (Larrosa et al., 2016).

Feedbacks occur when social or ecological responses to an intervention have an effect on intended outcomes, either directly or indirectly (Miller et al., 2010). The majority of research on feedbacks in conservation has been on either human or natural systems (Liu et al., 2007). Ecological mechanisms that lead to feedbacks have been widely studied within resource management (Altieri et al., 2013; Holling and Meffe, 1996), and have been integrated into conservation planning for resource management and restoration (Williams and Johnson, 2013). Dynamic optimisations explore how to use resources optimally over time, while accounting for the dynamic nature of systems. Social processes included in feedbacks from interventions have been less quantified in conservation, except for mechanisms related to land markets (Lim et al., 2016), which are mostly studied in the context of conservation planning and reserve selection (Armsworth et al., 2006; Butsic et al., 2013). Despite these studies, the impact of

49   accounting for feedbacks on conservation planning outcomes remains unresolved,

50   with some studies showing that planning for feedbacks improves project cost-

51   effectiveness (Crouzeilles et al., 2015; Toth et al., 2011), whilst in others the benefits

52   were not so clear (Butsic et al., 2013). The joint effect of social and environmental

53   feedbacks has yet to be assessed.

54   The nature of a conservation intervention plays a crucial role in determining the

55   feedbacks which may affect its outcomes (Armsworth et al., 2006). For example,

56   conservation interventions that change or restrict land use can increase land prices by

57   modifying the supply and demand for land and agricultural commodities (Lim et al.,

58   2016). This could lead to higher future land purchase costs, increasing overall cost of

59   the programme or affecting ecological outcomes when budget is limited. Similar

60   feedbacks could result in market failure, which is when the market does not efficiently

61   allocate goods and services (Mas-Colell et al., 1995). In conservation settings, market

62   failure often leads to under-provision of public goods such as biodiversity and

63   externalities, when those causing damage do not bear the costs (Kemkes et al., 2010;

64   Pascual et al., 2014). Despite the relevance of market failure to conservation, few

65   quantitative studies have explored it as a feedback mechanism (Wang and Miko,

66   1997).

67   Asymmetric information is one mechanism for market failure (Akerlof, 1970) that could

68   underpin feedbacks of conservation interventions. For example, when signing

69   contracts for conservation, landowners know better than programme administrators

70   how participation in conservation actions could affect their production plans and profits

71   (White and Hanley, 2016). The income lost by adopting conservation actions

72   compared to current income is the opportunity cost. If the opportunity cost is lower

73 than the compensation payment, there is an economic incentive to hide the real cost

74 of participation to extract additional revenue. This additional revenue is called

75 information rent. Information rent captured by landowners represents an extra income

76 that increases their net returns per hectare, similarly to an agricultural subsidy which

77 provides a direct payment that is not linked to production. These agricultural subsidies

78 have been shown to increase price of farmland, and even impact rural allocation of

79 land (Latruffe and Le Mouël, 2009; Patton et al., 2008). An incentive payment to set

80 aside farmland could therefore result in higher future payments and increase overall

81 project cost, because subsequent conservation payments need to approximately

82 match the rising opportunity cost of setting aside land in order to attract farmers to the

83 scheme (Fig.S1).

84 Information rent capture has been discussed in the conservation literature as

85 something to be minimized to increase efficiency of incentive-based conservation

86 (Ferraro, 2008; Mason and Plantinga, 2013). Methods to reduce information rent

87 capture include estimating attributes that determine the real cost of participating in

88 conservation and using these to calculate payments, as well as designing contracts in

89 a way that reveals participants' real costs. These methods can be costly and the

90 consequent gains in programme efficiency are variable (de Vries and Hanley, 2016;

91 Ferraro, 2008). Additionally, achieving fairness can be challenging in schemes that

92 include contracts with revelation mechanisms, such as auctions (Narloch et al., 2013).

93 The benefits of using information rent capture reduction methods might therefore be

94 negated at large scales due to the associated increasing costs, or when issues of

95 fairness are considered. In this context, understanding how to manage information

96 rent capture in spatial conservation planning at large scales is particularly important

97 for effective conservation programmes.

98   Here we present the first modelling approach to spatial conservation planning that

99   simultaneously accounts for both environmental and social feedbacks to prioritise a

100   large-scale set-aside programme. The approach modelled both forest connectivity and

101   incentive payment feedbacks within a conservation planning approach, designed

102   considering real world uses of optimisation tools (Pressey et al., 2013). We tested it

103   on a case study of ecological set-asides on private farmlands as a strategy for large-

104   scale forest restoration in Brazil. We compared prioritisation outcomes for both the

105   proposed approach and an established static one-off approach, and characterised

106   information rent capture.

Materials and Methods

1. Case study

Our case study area was the Brazilian Atlantic forest (BAF) region, a highly fragmented key global biodiversity hotspot (Sloan et al., 2014) that provides ecosystem services to ~70% of Brazilian population (Joly et al., 2014). Forest restoration and increasing forest connectivity are crucial to ensure that biodiversity-derived ecological functions are provided across the region (Banks-Leite et al., 2014). Ongoing restoration efforts include the Atlantic Forest Restoration Pact, a multi-sectoral coalition with the goal of restoring 15 million ha of Brazilian Atlantic Forest by 2050 (Pinto et al., 2014). In this case study, the aim was to set aside enough farmland to meet both a forest restoration target and connectivity increment target, at minimum possible cost.

2. Overview of the modelling approach

The main component of our approach was a spatial prioritisation exercise based on a widely used static approach (Fig. 1, steps 1 to 4). The proposed approach (from now on the "iterative" approach) integrates system's dynamics into the planning process by incorporating both an environmental and an economic feedback resulting from implementing agricultural set-asides (Fig.1, grey arrows). The environmental feedback modelled the effect that agricultural set-aside allocation has on forest connectivity. The economic feedback modelled the effect that allocation of payments for agricultural set-aside has on future payment price through informational rent capture. In the following sections methods are explained in detail; see supplementary materials (SM) text section 1 for a list of assumptions and section 2 for data and software used.

6

3. Scales and units

We used a nine-year time horizon, meaningful both for forest regeneration (Metzger et al., 2009) and programme commitment. Conservation interventions at such scales are commonly implemented in phases; in our study time moved forward in steps, each time-step representing three years (Fig. S1). In the static approach (from now on "one-off" approach), we ran one spatial conservation planning exercise one to meet forest connectivity and restoration targets. The solution was implemented in three parts to match the defined 3-year time-steps by dividing total restoration allocation for all priority areas into three parts. In the iterative approach, we divided the restoration target in three and ran one spatial conservation planning exercise at each time step to meet each third of the total restoration target. Solution implementation followed each prioritisation exercise, enabling the iterative approach to respond to feedbacks by adding new priority areas as payment value and connectivity changed at each time-step. Once a priority area was included for restoration it remained so until the end of the programme.

We used three spatial scales of relevance: municipality, biogeographical subregion, and whole Brazilian Atlantic Forest biome (BAF). The smallest unit of analysis was a municipality, because it is meaningful in policy terms, and a good compromise between ecological and social data available (Table S1). All municipalities that had at least 10 ha of forest within them were included in the analysis (SM Text, Section 3). Approximately 3,400 municipalities were included, covering an area of 212M ha. We grouped municipalities by 8 biogeographical subregions (from now on subregions) that span the BAF. Targets were set at subregional level to ensure their representation in

152　priority areas and maximize beta diversity for the whole biome (after (Tambosi et al.,

153　2014)). Targets were calculated at subregional level.

154　**4. Spatial conservation planning exercise**

155　We had two conservation targets: a restoration target, and a forest connectivity target,

156　to be met at minimum possible cost. Specifically, the objective function was:

$$\text{minimise} \sum_{ik=1}^{m_k} c_{ik} x_{ik},$$

157　　　　　　　　　　　　　　　　　　　　　　　　　　　　(Eq. 1)

158　subject to the constraint that both conservation targets (T_j) were met as follows:

$$\sum_{ik=1}^{m_k} A_{ijk} x_{ik} \geq T_{jk} \quad \forall jk$$

159　　　　　　　　　　　　　　　　　　　　　　　　　　　　(Eq. 2)

160　where m_k is the total number of municipalities in a given subregion k, c_{ik} is the cost of

161　including set-asides (effectively the opportunity cost of the area of farmland set aside)

162　for municipality i in subregion k, x_{ik} is the binary decision variable indicating whether

163　municipality i is selected ($x_{ik} = 1$) or not ($x_{ik} = 0$) for the solution group in subregion k,

164　and A_{ijk} is the contribution of municipality i to target j in subregion k. Units for A_{ijk} are

165　in hectares for both restoration and connectivity targets.

166　The prioritisation exercise involved four steps: (1) calculation of base metrics, (2)

167　calculation of prioritisation inputs, (3) spatial prioritisation, and (4) solution assessment

168　and implementation. For the iterative approach, base metrics (step 1) were updated

169　at each time-step based on feedbacks' models (section 5, below) before running steps

170　2 to 4 again. Figure 1 shows how all steps and metrics involved are linked.

171   Step 1: calculation of base metrics

172   These calculations were the first step towards both prioritisation approaches. In the

173   iterative approach two of these metrics (forest connectivity and farmland opportunity

174   cost) were re-calculated at time-steps 2 and 3.

175   *Potential set-aside area (PSA, ha)*

176   For all forest patches, we delimited a one-kilometre buffer area where set-asides could

177   potentially occur; set-asides were restricted to this potential set-aside area (PSA). This

178   distance is a threshold for natural regeneration in the BAF (Scervino and Torezan,

179   2015).

180   *Forest connectivity* (*ECA(IIC), ha*)

181   We used a graph theory approach to evaluate landscape connectivity, due to its

182   simplicity of representation, robustness, predictive power, and high potential to

183   incorporate connectivity functional attributes (Urban and Keitt, 2001). The integral

184   index of connectivity (IIC, (Pascual-Hortal and Saura, 2006)) is recommended as the

185   best binary index for the type of connectivity analysis performed (Saura and Pascual-

186   Hortal, 2007), and has been applied in many conservation planning case studies

187   (Saura et al., 2011a).

188   To calculate IIC, each municipality plus a 1-km buffer was depicted as a graph in which

189   existing forest patches are the nodes, patch area is used as the node's attribute, and

190   biological information on organisms' dispersal capability is used to define links

191   between nodes, which represent functional connectivity. *IIC* ranges from 0 to 1 and

192   increases with improved connectivity. It is given by:

193

$$IIC = \frac{\sum\limits_{i=1}^{n} \sum\limits_{j=1}^{n} \frac{a_i a_j}{1 + nl_{ij}}}{A_L^2}$$

(Eq. 3)

194   where n is total number of forest patches in the municipality, a_i and a_j are the sizes of

195   patches i and j, nl_{ij} is the number of links between patches i and j, and A_L is total

196   landscape area (comprising both habitat and non-habitat patches). A link exists when

197   the shortest path distance (topological distance) between patches is equal or smaller

198   than a dispersal distance. For nodes that are not connected the numerator in the

199   equation for IIC equals zero ($nl_{ij}=\infty$). When $i=j$ then $nl_{ij}=0$; this relates to habitat

200   availability (reachability) concept that applies for IIC, in which a patch itself is

201   considered as space where connectivity exists. When all landscape is occupied by

202   habitat, then $IIC=1$.

203   IIC uses species' dispersal distance to calculate functional connectivity. For this case

204   study, we used 200 meters as the dispersal capability based on an assessment of IIC

205   to various dispersal capabilities under a similar scenario (Tambosi 2014). Results

206   showed that using a dispersal capability of 200 m resulted in a restoration strategy

207   similar to that of using various dispersal groups (SM Text, section 4).

208   We used the Equivalent Connected Area (ECA(IIC), henceforth "connectivity") which

209   is preferable to IIC as a summary of overall connectivity because it has area units, it

210   is easier to interpret, and has a more usable range of variation (Saura et al., 2011b).

211   ECA(IIC) is calculated as the square root of the numerator of IIC, and it represents the

212   size that a single forest habitat patch should have in order to provide the same value

213   of IIC as the actual forest habitat pattern in the landscape (Saura et al., 2011a).

214   *Farmland opportunity cost (R, US$/yr) per year*

215   Farmland opportunity cost is the income forgone by setting aside land; in our case

216   study, income foregone from production or rent. We used farmland price data to

217   estimate farmland yearly rent extraction (Eq. 4), which is a proxy for opportunity costs

218   (Ferraro, 2008).

219                           $R_i = P_i \, r$ (Eq. 4)

220   where R_i is farmland rent extraction (from now on opportunity cost) for municipality *i*,

221   P_i is price of farmland in municipality *i*, and *r* is the discount rate (annual deposit

222   interest rate of 7.8% for Brazil in 2013, (The World Bank, 2013).

223   Step 2: calculation of prioritisation inputs

224   The prioritisation requires 5 input metrics. Two are targets, restoration and

225   connectivity. The remaining three inputs are based on metrics calculated in step one:

226   amount of set-aside, forest connectivity increment, and cost. In the iterative approach,

227   the two latter are updated at each time-step with the new base metrics accordingly

228   (Fig.1).

229   *Restoration Target*

230   The restoration target in number of hectares was calculated as restoring an area

231   equivalent to 15% of current BAF forest extent, which amounts to a total of 2.68 million

232   hectares. The BAF is a heavily degraded biome (Banks-Leite et al., 2014; Sloan et al.,

233   2014), and under the Convention on Biological Diversity's Aichi Targets Brazil is

234   committed to restoring at least 15% of degraded ecosystems by 2020 (National Target

235   15, www.cbd.int).

236   *Forest Connectivity Target*

237   For each subregion we calculated total potential forest connectivity increment for the

238   restoration target, and set forest connectivity target to 90% of that total. This was

239   defined by a sensitivity analysis to allow for flexibility for the algorithm in finding

240   solutions (SM text section 5). Higher percentage values did not allow for diversity in

241   solutions, and lower percentage values were just as cost-effective as the 90%

242   threshold value. Because total potential forest connectivity depends on existing

243   connectivity, in the iterative approach connectivity target had to be updated at each

244   time-step based on new forest connectivity values.

245   *Amount of set-aside (SA)*

246   Amount of set-aside (SA) was calculated as the set-aside required to meet the

247   restoration target, limited to potential set-aside area (PSA) and available farmland for

248   each municipality. This value effectively determines municipalities' contribution to the

249   restoration target. In the iterative approach total SA was divided into 3 equal parts so

250   at each time-step SA was the same, i.e., if a municipality was prioritised at all time-

251   steps it's contribution to the restoration target was total municipality's SA.

252   *Forest connectivity increment (dIIC)*

253   Forest connectivity increment was defined as the increment in forest connectivity

254   promoted by set-aside allocation, and determines municipalities' contribution to the

255   connectivity target. Given the analysis unit, and because it is unrealistic to determine

256   exact geographical location of each 10-ha set-aside, we used forest increment

257   simulations to measure uncertainty around the connectivity increment accrued by set-

258   asides. Forest connectivity increment (dIIC) estimation involved two steps: (i) forest

259   increment experiments, and (ii) calculation of changes in ECA(IIC). Forest increment

260   experiments consisted of simulating the creation of 10-hectare patches of forest

261   randomly 100 times within each municipality's potential set-aside area (PSA).

262   Simulations were run for cumulative levels of set-aside amounts corresponding to one,

263   two and three thirds of the municipalities' total amount of set-aside (SA). We calculated

264   dIIC in each municipality i for amount of set-aside j using forest increment simulation

265   k such that:

266   (Eq. 5)

267   where $dIIC_{ijk}$ is forest connectivity increment for municipality i promoted by the amount

268   of set-aside j for forest increment simulation k. We calculated average dIIC per

269   municipality and SA, with its standard error. Uncertainty was aggregated using

270   minimum, mean and maximum values of 95% adjusted bootstrap percentile

271   confidence intervals. In the one-off approach dIIC for a municipality was dIIC accrued

272   by total SA. In the iterative approach dIIC at any given time-step depended on whether

273   the municipality received SA in previous time-steps or not.

274   *Cost*

275   The cost of including each municipality in the set-aside programme was calculated as

276   the annual farmland opportunity cost per hectare (R, eq. 4), multiplied by the set-aside

277   area (SA) for each municipality and number of years within the programme.

278   Step 3: spatial prioritisation

279   We used Marxan to define which municipalities needed to be included in the

280   programme to meet defined restoration and connectivity targets at minimum cost.

281   Marxan uses simulated annealing, a probabilistic search heuristic commonly used to

282   find near-optimal solutions for functions that are hard to optimize with deterministic

283   methods (Maucher et al., 2011). We set Marxan to find 1000 solutions to the objective

284   function (Eq.1). Algorithm calibration and sensitivity analyses were run to get robust

285   results (SM Text, Section 5) following the Good Practices Handbook (Ardron et al.,

286   2010).

287   Marxan has two spatial output files, the "best" solution and the "summed" solution. The

288   former is the most cost-effective solution, the "summed" solution shows selection

289   frequency for each municipality. The selection frequency counts how many times

290   across the solutions space a municipality was chosen to be part of a solution. A

291   "robust" solution was created by choosing municipalities sequentially by selection

292   frequency (starting with the highest) until both conservation targets were met. This

293   was the final solution that identified municipalities in the set-aside programme.

294   Step 4: solution assessment

295   For all solutions, target achievement was assessed at biogeographical subregion

296   level.

297   **5. Modelling Feedbacks**

298   *Forest connectivity feedback:*

299   Priority areas for farmland set-asides depend on existing forest cover and connectivity

300   (Fig.1). Set-aside allocation in the previous time-step potentially modifies these

301   attributes, which need to be updated before finding the new priority areas. Because

302   forest increment simulations were run for all cumulative set-aside levels in each

303   municipality, forest connectivity (ECA(IIC)) and connectivity increment (dIIC) values

304   were obtained for all possible restoration allocations for each municipality. These

305   included receiving a restoration allocation once (at any time step), twice (at any two

306   time-steps), thrice (at all time-steps), or never. The new ECA(IIC) and dIIC values after

307   reforestation took place were obtained from the already calculated values, and

308   depended on whether it was the first, second or third time that a municipality had

309   received a set-aside allocation.

310   *Incentive payment feedback:*

311   In the case study, the programme offered a municipality-specific level of payment to

312   set aside farmland, set at the average opportunity cost of farmland in that municipality

313   (R). We calculated opportunity cost (R, Eq. 4) based on empirical observations of

314   farmland prices (SM Text section 2) and created frequency histograms to estimate the

315   probability distribution of opportunity costs for each municipality $F(q)$ (SM Text section

316   6). *Total information rent capture (U)* for municipality *i* was given by:

$$U_i = \sum_{i=1}^{i=n} \sum_{j=1}^{j=b} v_{ij} (\widetilde{\theta}_i - \theta_{ij}) q_i$$

317   (Eq. 6)

318   where *i* denotes municipality, $\widetilde{\theta}_i$ is mean opportunity cost of farmland for municipality

319   *i*, q_{ij} and n_{ij} are the opportunity cost value and its probability for bin *j* in municipality *i*

320   respectively, and q$_i$ is the amount of farmland being set-aside in municipality *i*. Total

321   information rent extracted in a municipality impacts average opportunity cost for that

322   municipality. That new opportunity cost ($\tilde{\theta}_{i_{(t+1)}}$), which is used to estimate payment (*p$_i$*)

323   for municipality *i* in the following time-step, was defined as:

324   (Eq. 7)

325   where *i* denotes municipality, *(t+1)* denotes subsequent time-step, is mean farmland

326   opportunity cost for municipality *i* at time-step *t*, $U_{i,t}$ is total information rent accrued for

327   municipality *i* at time-step *t*, and $q_{i,t}$ is total amount of farmland set aside in municipality

328   *i* at time-step *t*.

329   **6. Modelling validation**

330   Model validation and verification were an integral part of model development to ensure

331   an accurate representation of the real system. These included checking (1) the data

332   for validity and consistency, (2) the validity of assumptions and conceptual model, (3)

333   programming and implementation was correct, and (4) the range of results compared

334   to other SCPs for the region (SM Text section 7).

335   **Results**

336   **Comparing performance of one-off and iterative approaches**

337   The iterative approach resulted in a lower overall programme cost as well as improved

338   cost-effectiveness. Total cost of meeting both targets was US$3,553 million ($ mill.)

339   for the iterative solution over the 9-year period. Accounting for the increment in

340   opportunity cost of land due to information rent capture, the real cost of the one-off

341   approach was $3,797 mill, but the planned estimated total cost was $3,480 mill., i.e.

342   there would be a deficit of $317 mill in implementing the one-off plan. The cost of

343   ignoring feedbacks was $244 mill. Overall, the cost of each hectare of farmland set

344   aside for restoration was 6.4% lower in the iterative approach. Set-aside cost-

345   effectiveness, defined as area of farmland set aside per dollar spent, also improved in

346   the iterative approach. For each dollar spent, the iterative solution resulted in 6.9%

347   more farmland set aside than the one-off solution. In the iterative approach, farmland

348   opportunity costs increased over time due to the economic feedback and cost was

349   updated at each time-step, allowing for the inclusion of the most cost-effective

350   municipalities.

351   In terms of ecological outcomes, accounting for the forest connectivity feedback

352   resulted in 37% more municipalities with improved forest connectivity. The highest

353   increases in forest connectivity per hectare at municipality level were also achieved in

354   the iterative solution (Fig. S2, Fig. S3c). At BAF level, for each hectare of land that

355   was set aside, increment in forest connectivity in the iterative solution was 2.5-4.9%

356   less than in the one-off solution. However, this value reflected the sum of total forest

357   connectivity increment across municipalities and not the forest connectivity metric at

358   the BAF level, as the scale of analysis did not allow for such a calculation.

359   At a subregional scale however, whether a one-off or an iterative approach performed

360   better varied with subregion and metric being assessed (Fig. 2, Table S3). Cost per

361   hectare was lower for the iterative solution in six out of eight subregions (by 1-29%).

362   A similar result was observed for set-aside cost-effectiveness, with improvements of

363   1-5%. For both cost per hectare and cost-effectiveness, the one-off approach

364   sometimes performed slightly better (1-3.4%). Forest connectivity increment per

365   hectare (i.e. the proportion of each set-aside hectare that directly contributed to forest

366   connectivity) was higher for the one-off solution in six out of eight subregions (by 1.7-

367   34.3%). Differences in connectivity cost-effectiveness were more evenly distributed,

368   with the iterative solution reaching higher values in three out of eight subregions (by

369   4.8-23%). Despite this variability, in general terms at subregional level the iterative

370   solution was better in terms of cost per hectare and set-aside cost-effectiveness, while

371   solutions were similar in terms of connectivity gain per unit (ha or $).

372   Variability in performance of approaches resulted from the distribution of municipalities

373   with varying forest fragmentation levels and opportunity costs. Florestas de Interior,

374   for example, is the largest (Table S4) and most degraded subregion, with high levels

375   of fragmentation (Tambosi et al., 2014). Additionally, it has the largest range in mean

376   municipality farmland opportunity cost (71-1,164 $/ha/yr), and the largest variability

377   within municipalities (s.d. of mean municipality farmland opportunity cost as a

378   proportion of the mean 01-1.14). These extreme circumstances explain why this

379   subregion was an outlier in many ways. The iterative approach was substantially better

380   than the one-off approach, 41% more cost-effective and 15-23% more cost-effective

381 in terms of connectivity. Both economic and environmental feedbacks were important

382 in this subregion. Municipalities in the one-off solution had initial low opportunity cost

383 and intermediate forest cover but large increases in opportunity costs from the

384 economic feedback. This resulted in lower cost-effectiveness compared to the iterative

385 solution, which in this region had a wide choice of intermediate forest cover and low-

386 cost municipalities to avoid the economic feedback and leverage the environmental

387 feedback.

Programme priority areas

389 Configuration of priority areas differed between one-off and iterative approaches

390 (Fig.3a). Of all municipalities included in either solution, only 26% were included in the

391 set-aside programme regardless of approach. Thirty-two percent of municipalities

392 were included only in the iterative solution, and 7% only in the one-off solution. These

393 proportions varied widely at subregional level (Fig.3b). For any given subregion, 6%-

394 40% of municipalities were always priority areas, 20%-50% were only priorities in the

395 iterative solution, and 0%-24% were only priorities in the one-off solution. Given a

396 target set-aside amount, subregions that have many municipalities with low farmland

397 opportunity costs are more likely to include a higher number of municipalities in the

398 iterative solution than subregions that have lower opportunity costs but only in a few

399 municipalities.

400 The one-off solution included 20-50% fewer municipalities than the iterative solution

401 in most subregions (Table S4). This difference was not explained by number of

402 municipalities in the subregion (Fig.S4).

Information rent capture

Accounting for the economic feedback resulted in lower cost and higher cost-effectiveness, with some subregional variability. Given that the mechanism by which farmland opportunity cost increased over time was information rent capture, we expected the iterative solution to result in lower information rent capture by landowners. However, we found the opposite; information rent capture was 34% higher for the iterative solution ($323.4 mill.) despite this solution having a lower cost. The proportion of each dollar spent captured in information rent was 43% higher in the iterative than the one-off solution. Even though variability was observed in percent difference in proportional information rent capture between subregions (11%-89%), information rent capture was always higher for the iterative approach (Fig. 2).There were more municipalities in the iterative solution for which information rent capture per hectare was higher, and for which difference between approaches reached higher values (Fig.S3b).

Discussion

418   We present the first approach to spatial conservation planning that accounts for both

419   ecological and economic feedback effects of a conservation intervention at its initial

420   stage. Both iterative and one-off approaches present solutions to the set-aside

421   allocation problem that meet the given targets within the set budget. Overall, however,

422   applying the iterative approach resulted in increased cost-effectiveness when

423   compared to a one-off approach, reinforcing results from other studies that form the

424   scarce empirical evidence on economic feedbacks in conservation planning (Butsic et

425   al., 2013). However, at subregional level the iterative approach resulted in a range of

426   cost-effectiveness improvements, and sometimes reductions. Dynamic conservation

427   planning studies using simulated data have also found that the extent to which

428   accounting for market feedbacks improved cost-effectiveness depended on system

429   and location characteristics (Armsworth et al., 2006; Dissanayake and Önal, 2011).

430   In terms of conservation outcomes, biodiversity benefits derived from forest

431   connectivity gains were higher for the iterative approach regardless of scale, because

432   more municipalities were included in the solution. As municipalities could not be

433   "dropped" of the programme, in going for the most cost-effective municipalities the

434   iterative approach engaged more municipalities. More municipalities participating in

435   forest restoration result in regenerating areas that are more widely distributed,

436   providing a buffer to uncertainty through a more spatially extensive network of

437   connected forest. This is key to preserving biodiversity in the BAF, as it is mainly

438   comprised of small isolated populations (Hatfield et al., 2018). More municipalities

439   participating in the set-aside programme could also benefit species with smaller

440   ranges that are currently not protected, because it is more likely that they will have

441   regenerating forest within their range. Furthermore, more people could benefit from

442   improved local-scale ecosystem services, such as pollination and soil retention

443   (Farley, 2012). However, the one-off approach resulted in higher connectivity per

444   hectare of land restored at both BAF and most subregional levels. These slightly

445   contradictory results can be explained by the non-linear relationship between forest

446   cover and forest connectivity, in which the same increment in forest cover results in a

447   larger connectivity increment the larger the base forest cover is (Rappaport et al.,

448   2015). Because in the one-off solution the same municipalities received sequential

449   set-aside allocations, forest connectivity gains for the same set-aside amount

450   increased over time.

451   Most literature on information rent in conservation focuses on the need to minimize its

452   capture to improve cost-effectiveness (Ferraro, 2008; White and Hanley, 2016). By

453   contrast, our results show that if information rent capture is allowed, increased capture

454   (and therefore higher incentives to participate) can be obtained without increasing

455   overall cost. In the iterative approach, Marxan provides the cheapest solution at each

456   time-step, regardless of information rent. Municipalities with lower farmland

457   opportunity costs are prioritised over ones with higher opportunity costs, even if the

458   former entail higher information rent capture than the latter. In this way, the iterative

459   solution both has a lower cost and allows more landowners to capture information rent.

460   Our results also suggested that under the iterative approach not only would a wider

461   range of landowners have an incentive to participate in the programme due to

462   information rent capture, but that incentives could also be higher.

463   Several studies have used contract design theory to show how auctions help reveal

464   hidden costs and avoid adverse selection, especially in the context of agri-

465   environmental policies (Latacz-Lohmann and Schilizzi, 2005). However, the prospect

466   of information rent capture acts as an economic incentive for programme participation

467   (Scheufele and Bennett, 2017). The iterative approach proposed in this study

468   estimates total information rent capture, which enables a comparison with the cost of

469   implementing revealed cost mechanisms for a large-scale programme. If these are

470   similar, information rent capture is no longer a "waste" of money as it is an unavoidable

471   cost transformed into an economic incentive. Given that asymmetric information is

472   bound to exist in the real world, especially at large scales, our approach could be a

473   new tool to get information rent capture working for conservation.

474   **Implications for conservation and decision-making**

475   Nowadays, rigorous planning methods are especially needed, given that collaborative

476   conservation action at landscape scales is on the rise and global financial crises

477   restrict conservation investments (Mazor et al., 2014). In our case study, ignoring the

478   economic feedback at the planning stage resulted in a total programme cost that was

479    $317 mill. higher than the estimated direct cost of meeting the restoration target using

480   a one-off approach. This difference is large enough that, if budget were fixed at the

481   originally estimated cost, the restoration target would not have been met.

482   Conservation on private lands plays a crucial role in conserving biodiversity in highly

483   fragmented areas (Paloniemi and Tikka, 2008), and this is particularly true for the

484   Brazilian Atlantic Forest where land owners have a legal requirement to set aside 20%

485   of their property for forest. Traditional regulation has not provided a complete solution

486   due to large numbers of private landowners and the hidden nature of their activities,

487   which has led to an increasing emphasis on offering financial incentives for

488   conservation (Stern, 2006). Conservation payments can either aim to compensate

489   costs, to change behaviour, or both (Vatn, 2010). Using the proposed iterative

490   prioritisation, the set-aside programme could move from being only a compensation

491   payment to providing an incentive to change behaviour, mostly by increasing

492   information rent capture without increasing cost of the programme. Higher levels of

493   information rent captured by more farmers, spread more evenly across more

494   municipalities, could prove to be an invaluable benefit of the iterative approach in

495   regions where there is low willingness to join this type of programme. Optimization

496   studies in the PES and spatial planning literatures have begun to incorporate

497   dimensions of equity (Halpern et al., 2013). Potential issues with large-scale set-aside

498   payments could be the inequitable distribution of costs (land-use restrictions) and

499   benefits (economic incentives); an iterative approach could reduce these issues. It

500   could also enhance distributional equity and increase perceived fairness, thereby

501   increasing probability of programme success (Pascual et al., 2014). A large region

502   such as the BAF, however, includes a wide range of socio-economic and land-use

503   rights profiles; the impact of local circumstances on equity would need to be further

504   explored.

505   **Future work**

506   Despite feedbacks being highlighted as needing more attention (e.g. Miller et al. 2010),

507   there has been limited quantitative exploration of feedbacks in conservation planning.

508   Here we present a method for incorporating environmental and economic feedbacks

509   into models to inform intervention design. Further work is needed if conservation

510   planners are to understand trade-offs in integrating varying levels of complexity of the

511   dynamics that are at play at multiple temporal and spatial scales. Uncertainty in

512 outputs for both approaches needs to be quantified to communicate reliability of results

513 to decision-makers. For our model, this can include further sensitivity analyses testing

514 the performance of the model for a range of discount rates and connectivity scenarios

515 (e.g. based on different dispersal distances). Application of the model to other case

516 studies for different geographies, targets, and conservation interventions, and

517 improvements in computational power will improve model's validation. These

518 improvements will provide a better understanding of circumstances and scales under

519 which the iterative approach improves cost-effectiveness over a one-off approach.

520 Increased spatially explicit socio-economic data availability will also help clarify

521 differences between approaches. For example, more realistic cost estimation would

522 be possible if the transaction costs associated with the set-aside program were known

523 (Zheng et al., 2013); these data did not exist for the case study area. More broadly,

524 there is a need to model other feedbacks, and test other tools to quantify these, such

525 as agent-based modelling (Huber et al., 2013) and systems dynamics (Elsawah et al.,

526 2017). Understanding which feedbacks are most relevant under various

527 circumstances is key to addressing the challenge of accounting for system dynamics

528 in conservation planning.

529

530 **Conclusion**

531 The proposed iterative approach to spatial conservation planning increased cost-

532 effectiveness at biome level, improved conservation outcomes, resulted in different

533 priority areas for farmland set-asides, and included more municipalities in the set-

534 aside programme. These results show important benefits from modelling, quantifying

535 and then planning for, feedbacks that inevitably accompany large-scale conservation

536 interventions. Additionally, by modelling information rent capture, the iterative

537 approach shows that information rent can be used as an existing economic incentive

538 for participation while still having lower overall cost. This could potentially re-define the

539 way in which conservation projects perceive information rent extraction, away from

540 minimization and towards utilising the opportunities that it provides.

541

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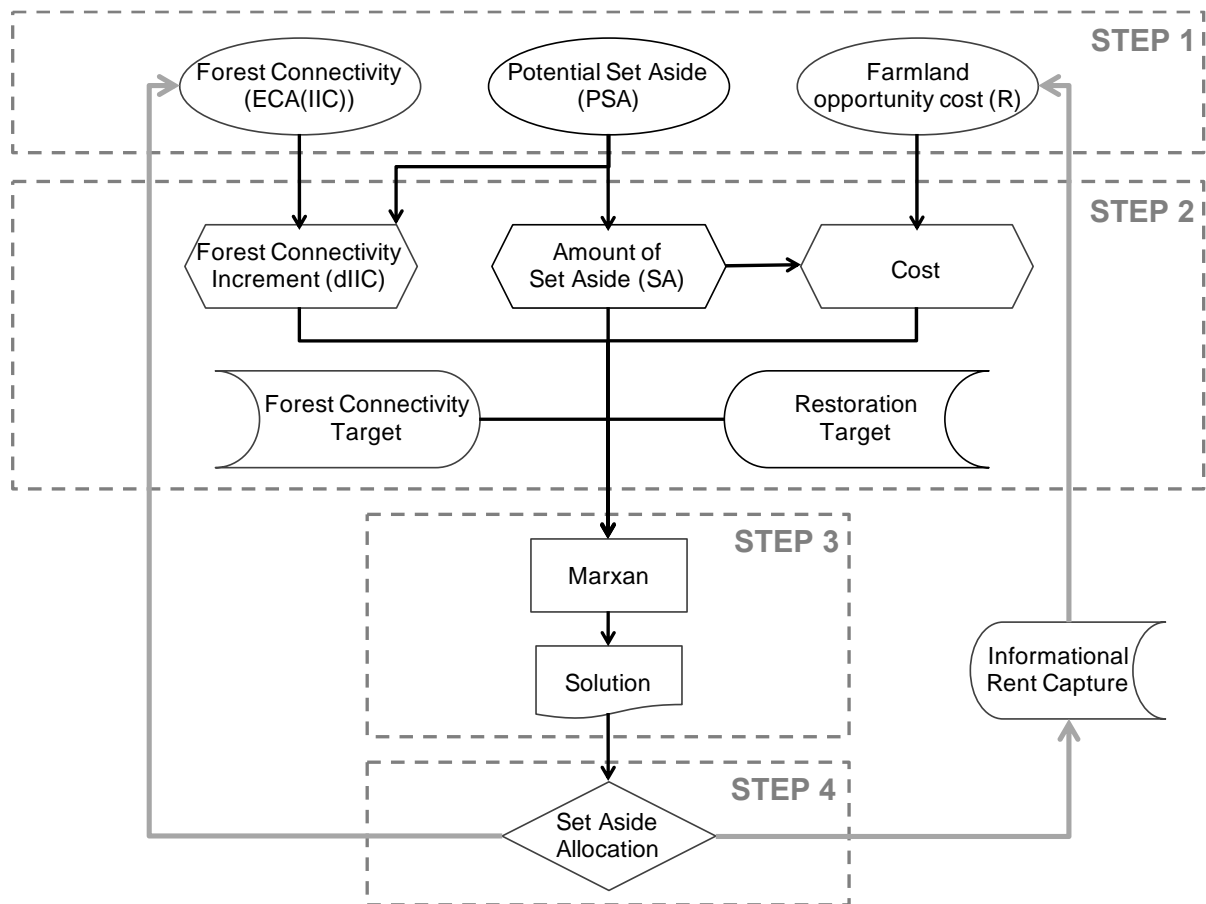686   https://doi.org/10.1016/j.landurbplan.2007.03.005

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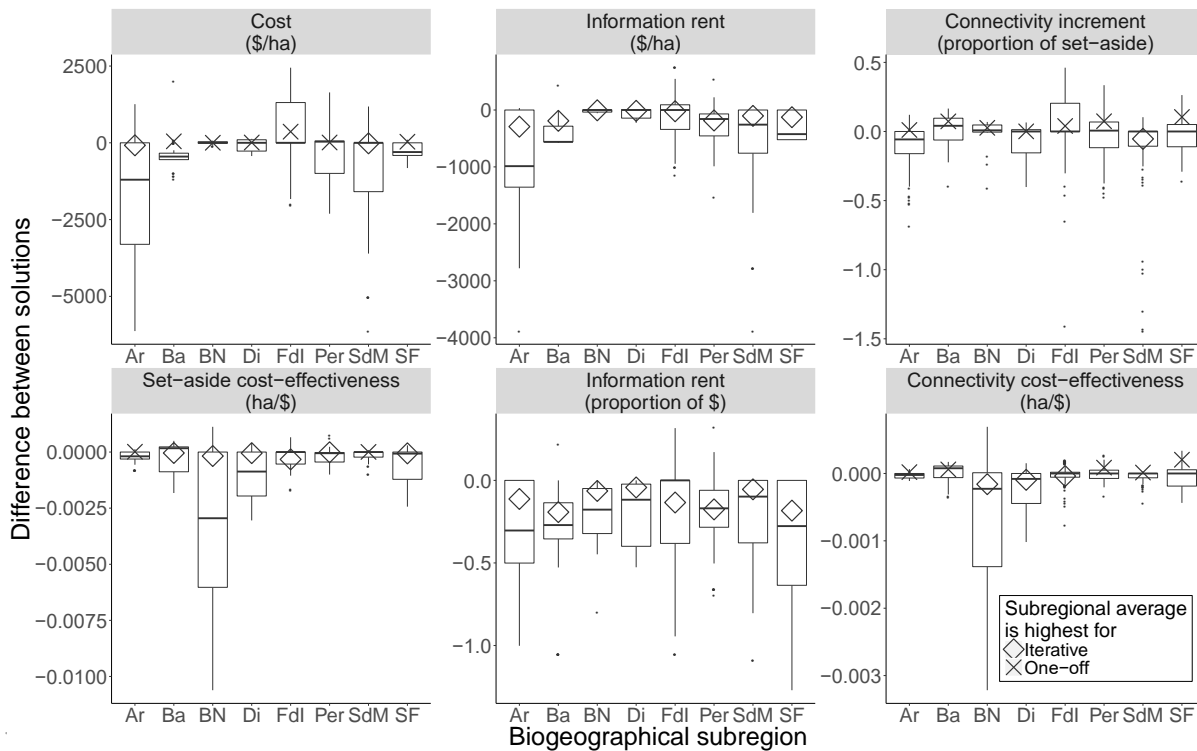691 Scervino, R.P., Torezan, J.M.D., 2015. Factors affecting the genesis of vegetation

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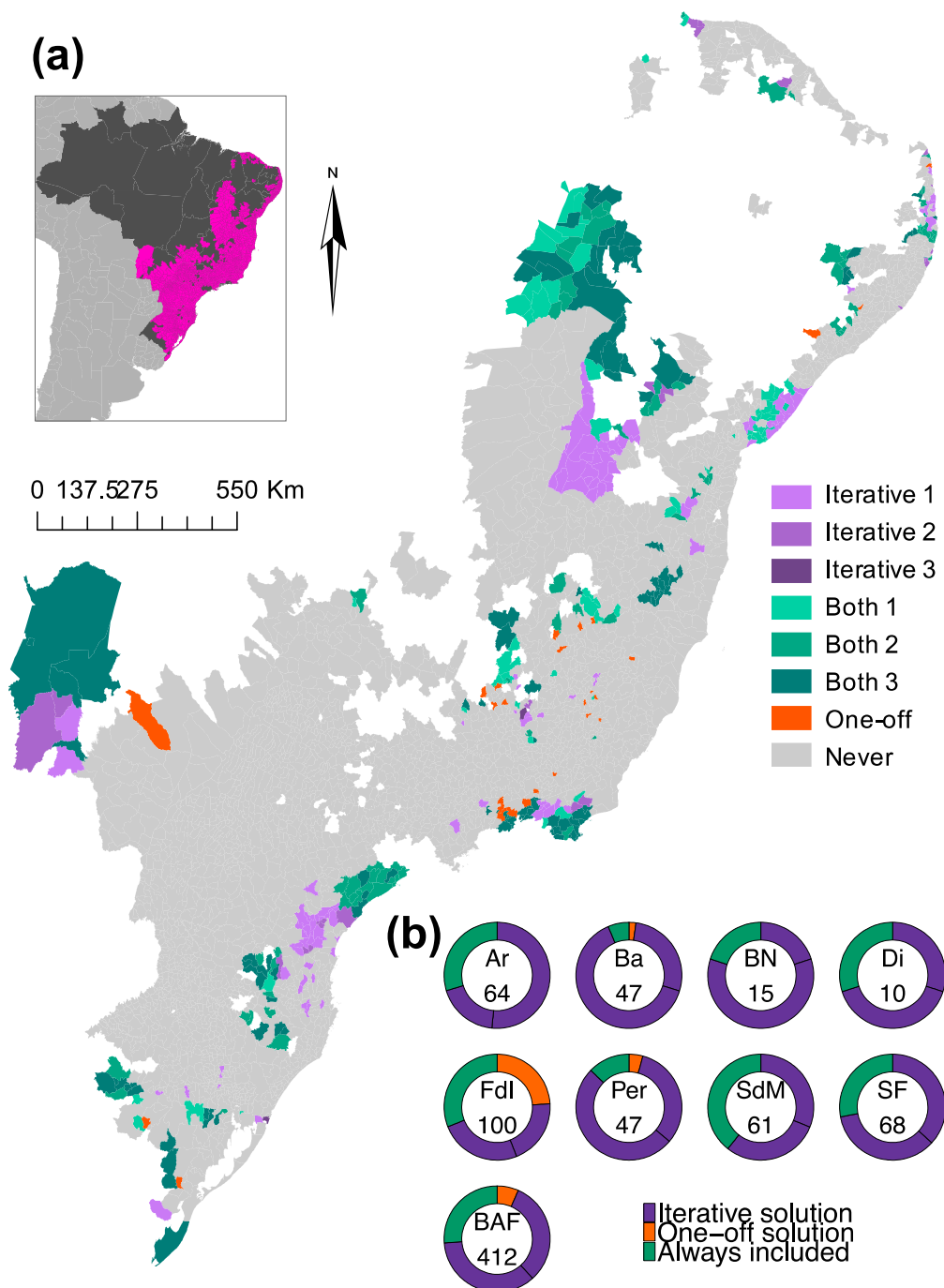728   Proc. Natl. Acad. Sci. U. S. A. 110, 16681–16686.

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730

731   **Figures**

732

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734   **Fig.1. Methodological framework for prioritisation approaches.** The one-off
735   approach involved steps 1 to 4: (1) calculation of base metrics from data, (2)
736   calculation of prioritisation inputs, (3) spatial prioritisation, and (4) solution assessment
737   and implementation. The iterative approach included updating metrics at step 1 before
738   moving on to next steps. Grey arrows show feedbacks, and all stages that are updated
739   are shaded in grey. Ovals denote starting points, hexagons denote preparation steps,
740   "D" shaped polygons indicate that information is coming into the process, rectangle
741   indicates a process, curved edged rectangle denotes an output, and rhombus
742   indicates a decision.

744

Fig.2. Distribution of differences in performance between one-off and iterative approaches. Boxplots show min, max, median and interquartile range of municipality-level observations. Crosses and diamonds show the mean difference at biogeographical subregion level. Diamonds reflect negative differences, in which the iterative solution has a higher value than the one-off solution. Crosses show the opposite. Biogeographical subregions: Florestas de Araucaria (Ar), Bahia (Ba), Brejos Nordestinos (BN), Diamantina (Di), Florestas de Interior (FdI), Pernambuco (Per), Serra do Mar (SdM), and Sao Francisco (SF). For Di, interval estimate for subregional mean connectivity increment crosses zero (-0.002,-0.004).

Fig.3 [to be printed in colour]. Municipalities included as part of a prioritisation solution: (a) spatial distribution. Categories: Iterative 1, 2, and 3 show municipalities included only in the iterative solution, once, twice or at all 3 time-steps respectively; Both 1, 2 and 3, show municipalities included in both the one-off and iterative solutions, once, twice or in all 3 time-steps of the iterative solution respectively; One-off shows municipalities included only in the one-off solution. In grey municipalities excluded from solutions. **(b)** The proportion of included municipalities for each category by subregion. Categories are simplified to one-off solution exclusively, iterative solution exclusively, and always included. Each ring represents a biogeographical subregion: Florestas de Araucaria (Ar), Bahia (Ba), Brejos Nordestinos (BN), Diamantina (Di), Florestas de Interior (FdI), Pernambuco (Per), Serra do Mar (SdM), and Sao Francisco (SF). The number shows municipalities included in any solution.