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E-mail: jaramarv@gmail.com**Keywords:** disaggregation of beneficiaries, ecosystem services, fair, spatial conservation prioritizationSupplementary material for this article is available [online](#)**Abstract**

Conservation decision-makers and practitioners increasingly strive for efficient and equitable outcomes for people and nature. However, environmental management programs commonly benefit some groups of people more than others, and very little is known about how efforts to promote equality (i.e. even distributions) and equity (i.e. proportional distributions) trade-off against efficiency (i.e. total net outcome per dollar spent). Based on a case study in the Brigalow Belt Bioregion, Australia, we quantified trade-offs between equality, equity, and efficiency in planning for flood protection. We considered optimal restoration strategies that allocate a fixed budget (a) evenly among beneficiary sectors (i.e. seeking equality among urban residents, rural communities, and the food sector), (b) evenly among local government areas (LGAs) within the Brigalow Belt (i.e. seeking spatial equality), and (c) preferentially to areas of highest socioeconomic disadvantage (i.e. seeking equity). We assessed equality using the Gini coefficient, and equity using an index of socioeconomic disadvantage. At an AUD10M budget, evenly distributing the budget among beneficiary sectors was 80% less efficient than ignoring beneficiary groups, and did not improve equality in the distribution of flood protection among beneficiary sectors. Evenly distributing the budget among LGAs ensured restoration in four areas that were otherwise ignored, with a modest reduction in efficiency (12%–25%). Directing flood protection to areas of highest socioeconomic disadvantage did not result in additional reductions in efficiency, and captured areas of high disadvantage for the rural and urban sectors that were missed otherwise. We show here that different ways of targeting equity and equality lead to quite different trade-offs with efficiency. Our approach can be used to guide transparent negotiations between beneficiaries and other stakeholders involved in a planning process.

1. Introduction

Urgent action is needed to protect, restore, and sustainably manage ecosystems to secure their benefits to people, commonly known as ecosystem services (box 1) (Chan and Satterfield 2020, Mandle *et al* 2020). Given limited resources available for management and conservation interventions, finding efficient solutions that achieve the greatest return on investment is crucial (Possingham *et al* 2001,

Moilanen *et al* 2009, Halpern *et al* 2013). However, such interventions may not result in a fair distribution of benefits for different groups of people across a planning region (Mandle *et al* 2015, Grima *et al* 2019, Gourevitch *et al* 2020). Furthermore, what is regarded as a 'fair' benefit distribution will vary according to underlying social, economic, and political conditions affecting peoples' opportunities to derive benefits (McDermott *et al* 2013, Vucetich *et al* 2018). Thus, there is strong need to develop

Box 1. Glossary.

Concept	Definition
Beneficiaries	People whose well-being is influenced by ecosystem services (Daw <i>et al</i> 2011, Keeler <i>et al</i> 2012).
Demand	Extent to which an ecosystem service is currently or potentially used, needed, or preferred by people (Villamagna <i>et al</i> 2013, Bagstad <i>et al</i> 2013).
Ecosystem Services	Biophysical and social conditions and processes by which people, directly or indirectly, obtain benefits from ecosystems that sustain and fulfill human well-being (MEA 2005, Daily 1997).
Efficiency	Total net outcome per dollar spent (Brown <i>et al</i> 2018, Halpern <i>et al</i> 2013).
Equality	Even distribution of ecosystem service benefits among beneficiaries (McDermott <i>et al</i> 2013).
Equity	Distribution of ecosystem service benefits according to different beneficiaries' opportunities to derive benefits (McDermott <i>et al</i> 2013).
Fair	Distribution of ecosystem service benefits according to well-reasoned application of three principles: equality (all humans are entitled to the same outcomes), need (what is necessary for realizing a healthy, meaningful life), and desert (noun form of deserve—benefit is distributed in proportion to peoples' contributions) (Vucetich <i>et al</i> 2018, McDermott <i>et al</i> 2013, Wagstaff 1994).
Flow	Biophysical or human capital-driven interactions and processes that connect supply and demand (Fisher <i>et al</i> 2009, Villamagna <i>et al</i> 2013).
Optimization problem	Mathematical formulation describing the problem of finding the best solution from all feasible solutions (Moilanen <i>et al</i> 2009).
Passive restoration	Method to assist the natural re-establishment of vegetation utilizing low-cost techniques such as restriction of livestock grazing or vegetation thinning to reduce competition and promote growth (Evans <i>et al</i> 2015).
Spatial planning	Structured decision analysis approach with a series of stages to meet specific objectives, usually through the prioritization of the most feasible places for conservation investment (Moilanen <i>et al</i> 2009).
Supply	Ecosystem conditions and processes that contribute to the potential delivery of a particular ecosystem service (Fisher <i>et al</i> 2009, Villamagna <i>et al</i> 2013).

spatial planning solutions that recognize the diversity of ecosystem service beneficiaries in a landscape and their different opportunities to access benefits (Chan and Satterfield 2020, Villarreal-Rosas *et al* 2020). In equal approaches, benefit is distributed evenly among beneficiaries, while in equitable approaches, benefit is distributed relative to peoples' opportunities to access ecosystem services (Daw *et al* 2011, McDermott *et al* 2013). Promoting fairness through equal and equitable planning strategies is likely to result in trade-offs with efficiency (Halpern *et al* 2013, Klein *et al* 2015, Brown *et al* 2018). Investigating these trade-offs is fundamental to guide fair conservation investments.

People's opportunities to obtain benefits from ecosystem services are influenced by the physical locations where people demand a service relative to the places where ecosystem services are supplied, and the flow mechanisms that enable the benefits of a service to be utilized by people (Haines-Young and Potschin 2010, Serna-Chavez *et al* 2014). For example, physical and mental health benefits from outdoor experiences are not distributed evenly across a landscape and, the distance between people's residences and the location of natural areas affects people's opportunities to benefit from recreation activities in nature (Sonter *et al* 2016, Martinez-Harms *et al* 2018, Dade

et al 2020). Underlying socioeconomic factors also influence people's ability to reach or benefit from a service, including people's access to ecosystem service substitutes, or their ability to overcome ecosystem service loss (Daw *et al* 2011, Wilkerson *et al* 2018, Vallet *et al* 2019). For example, in the US, Latino and African American residents live in areas with low access to urban green space, where heat island effects are felt more strongly, yet, such minority groups usually have less economic opportunity to pay for air conditioning (Nesbitt *et al* 2019, Hoffman *et al* 2020).

Addressing inequalities through management or conservation intervention requires developing planning strategies that acknowledge benefit is distributed differently amongst people (Daw *et al* 2011, Chan and Satterfield 2020, Villarreal-Rosas *et al* 2020). Yet, to date, most planning approaches for ecosystem services have focused on obtaining total benefit gains (Villarreal-Rosas *et al* 2020). That is, the sum of all the benefits regardless of to whom those benefits flow or if local benefit decreases occur, which overlooks the variation in the flow of benefits among people (Daw *et al* 2011, McDermott *et al* 2013). Some studies have started to explore this issue when planning for ecosystem services. For example, Gourevitch *et al* (2020) and Li *et al* (2020) found that floodplain restoration

is an economically viable intervention to reduce flood damage, although mitigation of flood risk benefited more the socioeconomically advantaged beneficiary sectors (Gourevitch *et al* 2020). This suggests that management plans seeking to benefit the most disadvantaged people in society may imply higher management costs, although the extent of such trade-offs has been understudied in the ecosystem services literature.

In this study, we aim to assess how efficiency is affected when promoting equality and equity in spatial planning, and we discuss how this information is useful to advance towards fair management plans for ecosystem services. We use as a case study the provision of flood protection in the Brigalow Belt, Australia. Flood protection is one of the most severely affected ecosystem services from land degradation, increasing the risk to life and property for millions of people globally (Pesaresi *et al* 2017). In the Brigalow Belt—an area affected by widespread deforestation—previous flood events have caused local damage to housing and infrastructure valued at over AU\$5 billion (State of Queensland 2019, Commonwealth of Australia 2020). Programs are available to assist with recovery after floods (Australian Government 2020), yet variation in income, education, employment security, and housing characteristics influence the capacity of rural and urban residents to benefit from these programs (Morrissey and Reser 2007, Veitch 2009).

A previous study in the Brigalow Belt identified highly disproportionate declines in flood protection across three beneficiary sectors due to forest loss (namely: urban residents, rural communities, and the food sector) (Villarreal-Rosas *et al* 2022). Investing in forest restoration constitutes a nature-based alternative to decrease flood risk, and has been shown to be an economically viable solution in other regions (Gourevitch *et al* 2020, Li *et al* 2020). Here, we develop different forest restoration investment strategies to address some of the previously identified disparities in the distribution of flood protection from forest cover among beneficiary sectors in the Brigalow Belt. Our three strategies for restoration investment include: promoting equality by (a) evenly distributing monetary resources among beneficiary sectors, or (b) evenly distributing monetary resources among local government areas (LGAs); and (c) promoting equity by giving priority to areas of high socioeconomic disadvantage. In this respect, we ask, to what extent do investment strategies improve equality and equity among beneficiary sectors, compared to a baseline strategy where these are ignored, and how is efficiency (the total flood protection obtained under different planning budgets) affected when promoting equality and equity of investment strategies?

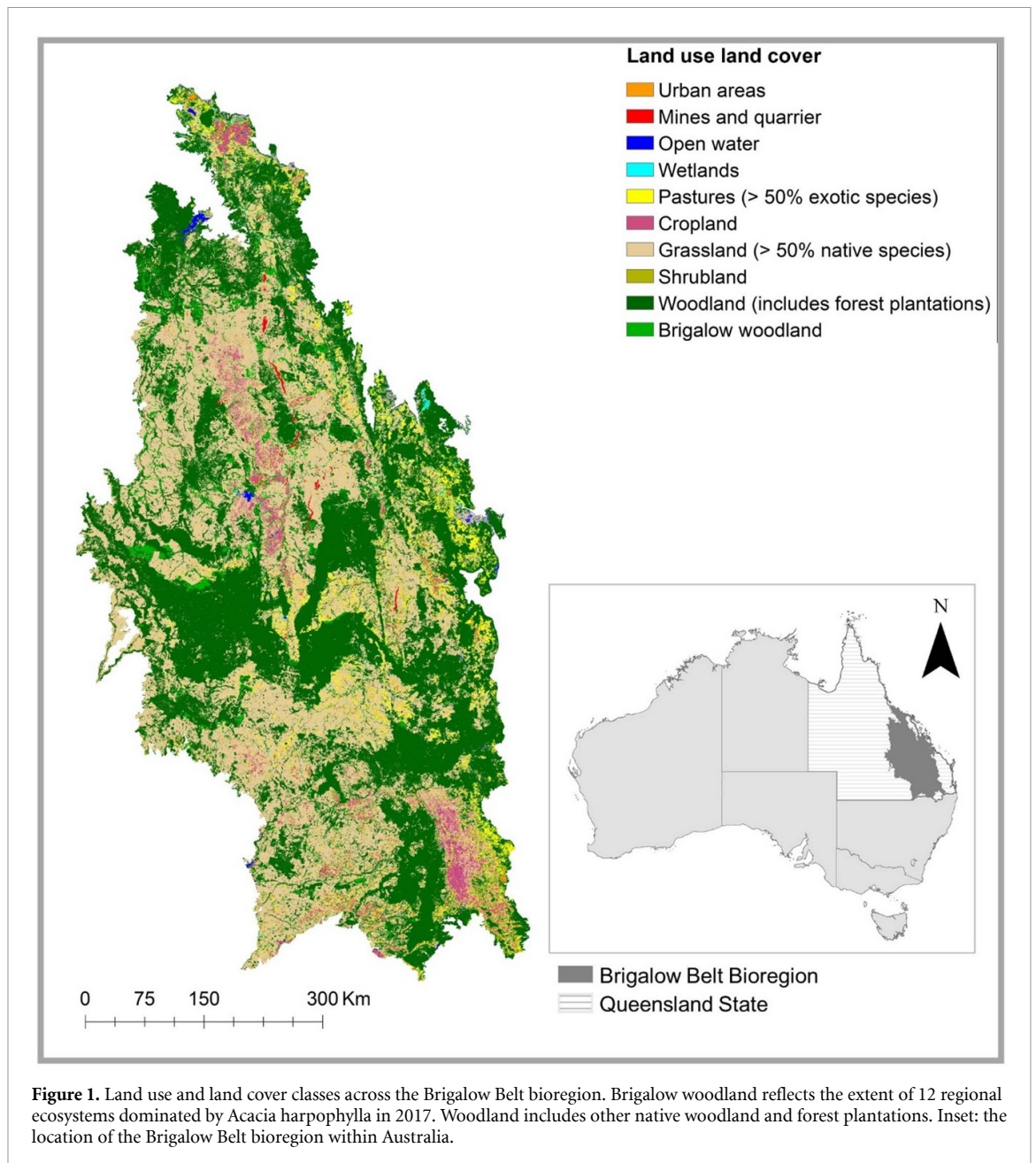
2. Methods

2.1. Study area

Forest cover loss reduces the capacity of ecosystems to regulate flood intensity, exacerbating damages to people from flood events (MEA 2005, IPBES 2019). The Brigalow Belt Bioregion (351 500 km²) located within the State of Queensland (figure 1) has had one of the highest deforestation rates in Australia in recent times (Evans 2016). The Brigalow Belt is named after the Aboriginal name for the region's dominant tree species *Acacia harpophylla* (Ponce Reyes *et al* 2016, Department of the Environment 2020). Notably, Brigalow trees sprout from the root stock in the soil (suckering) following disturbance (Chandler *et al* 2007). Despite broad scale clearing of Brigalow forest in some regions, much of the cleared land retains regenerative capacity (Butler 2009, Lucas *et al* 2014). This is particularly true in areas of extensive grazing, where clearing of regrowth is a common management practice for landholders (Butler 2009, Dwyer *et al* 2009, Fensham and Guymer 2009). Thus, promoting regrowth of Brigalow forest constitutes an alternative for the restoration and maintenance of ecosystem function (Dwyer *et al* 2009, Evans *et al* 2015). Promoting vegetation regrowth is a passive restoration method that requires little intervention, as such, it represents a low cost and highly efficient restoration alternative (Dwyer *et al* 2009, Evans *et al* 2015). However, allowing regrowth implies foregone revenue for farmers (Evans *et al* 2015).

2.2. Investment strategies

We first defined an optimization problem to find the best places to invest in passive restoration of Brigalow forest to enhance flood protection for three beneficiary sectors: urban residents, rural communities, and the food sector (box 2). In our optimization problem, enhancing flood protection for each beneficiary sector represented a sub-objective; all sub-objectives were incorporated as an equally weighted sum into the objective function (box 2). We used cadastral lots from the Queensland cadastral dataset (Department of Natural Resources, Mines and Energy 2018) as decision units (with a total of 18 863) where passive restoration was allocated to. Selection of decision units was constrained by budget levels that represented 3%–50% of the total opportunity cost (the cost of grassland turning into Brigalow regrowth) for extensive grazing in the Brigalow Belt (\$340 M AUD per annum). We considered this set of predefined budgets to explore changes in the amount of flood protection captured at different expenditures. We then used the restoration opportunities optimization tool (Beatty *et al* 2018) to solve the optimization problem (table S1 for full details (available online at stacks.iop.org/ERL/17/014001/mmedia)).



Decision units comprised locations where passive restoration is feasible to apply independently of benefits or costs (table S1). We calculated flood protection at the decision unit level, as the marginal reduction value in quickflow production after intervention multiplied by the sum of all downstream demand for flood protection the decision unit had access to. Reductions in quickflow after intervention were estimated using the InVEST 3.5.0 Seasonal Water Yield model (table S1). Demand for flood protection was estimated as the area and number of infrastructure at risk of flooding at the downstream floodplain areas of sub-watersheds identifying each beneficiary sector (table S1). Demand values for each beneficiary sector were aggregated to decision units as the sum of demand of all the sub-watersheds that overlapped with a given decision unit (table S1). Decision units often provided benefit to more than one beneficiary

sector. Decision units were associated to LGAs using the 'Local Government Area Boundaries Queensland' dataset (Department of Natural Resources, Mines and Energy 2019).

We developed different investment strategies to solve this optimization problem (i.e. different objective functions, box 2). Our investment strategies aim to address previously identified inequalities in the distribution of flood protection among multiple beneficiaries and LGAs in the Brigalow Belt (Villarreal-Rosas *et al* 2022). Therefore, our first two investment strategies promoted equality by constraining how restoration resources are allocated among beneficiary sectors or among LGAs (table 1). Then, we accounted for equity in our investment strategies by giving preference to locations of high socioeconomic disadvantage. We also considered a 'baseline' investment strategy for

Box 2. Objective functions and constraints used for each investment strategy.

baseline

$$\begin{aligned} & \min \sum_{i=1}^n w_i \sum_{j=1}^m p_{ij} x_j \\ & \text{subject to} \\ & \sum_{j=1}^m c_j x_j = T \end{aligned}$$

w_i = weight assigned to each beneficiary sector i

p_{ij} = flood protection for each beneficiary sector i in decision unit j , where

$$p_{ij} = s_j d_{ij}$$

s_j = marginal reduction value in quickflow production after intervention in decision unit j

d_{ij} = demand value per beneficiary sector i in decision unit j

c_j = the opportunity cost in decision unit j

x_j = binary (1/0) decision variable (passive restoration) to allocate in decision unit j

T = budget constraints (3,5,10,20,30,40,50% of the total opportunity cost)

sectors

$$\begin{aligned} & \min \sum_{i=1}^n w_i \sum_{j=1}^m p_{ij} x_{ji} \\ & \text{subject to} \\ & \sum_{j=1}^{m_i} c_{ji} x_{ji} = T_i \text{ for all } i = 1, \dots, z \end{aligned}$$

$$p_{ij} = p_{ij} = s_j d_{ij}$$

x_{ji} = binary (1/0) decision variable (passive restoration) to allocate in decision unit j associated to each beneficiary sector i

m_i = decision units associated to each beneficiary sector i

c_{ji} = the opportunity cost in decision unit j associated to each beneficiary sector i

T_i = budget constraints applied to each beneficiary sector i , where 3,5,10,20,30,40,50% of the total opportunity cost is equally allocated across sectors

sectors + disadvantage

$$\begin{aligned} & \min \sum_{i=1}^n w_i \sum_{j=1}^m p_{ij} x_{ji} \\ & \text{subject to} \\ & \sum_{j=1}^{m_i} c_{ji} x_{ji} = T_i \text{ for all } i = 1, \dots, z \end{aligned}$$

p_{ij} = flood protection for each beneficiary sector i in decision unit j , where

$$p_{ij} = s_j d_{ij} e_{ij}$$

s_j = marginal reduction value in quickflow production after intervention in decision unit j
 d_{ij} = demand value per beneficiary sector i in decision unit j

e_{ij} = index of socioeconomic disadvantage per beneficiary sector i in decision unit j

LGA

$$\begin{aligned} & \min \sum_{i=1}^n w_i \sum_{j=1}^m p_{ij} x_{jg} \\ & \text{subject to} \\ & \sum_{j=1}^{m_g} c_{jg} x_{jg} = T_g \text{ for all } g = 1, \dots, z \end{aligned}$$

$$p_{ij} = p_{ij} = s_j d_{ij}$$

x_{jg} = binary (1/0) decision variable (passive restoration) to allocate in decision unit j within Local Government Areas g

m_g = decision units within Local Government Areas g

c_{jg} = the opportunity cost in decision unit j within Local Government Areas g

T_g = budget constraints applied to each Local Government Area g , where 3,5,10,20,30,40,50% of the total opportunity cost is equally allocated across Local Government Areas

LGA + disadvantage

$$\begin{aligned} & \min \sum_{i=1}^n w_i \sum_{j=1}^m p_{ij} x_{jg} \\ & \text{subject to} \\ & \sum_{j=1}^{m_g} c_{jg} x_{jg} = T_g \text{ for all } g = 1, \dots, z \end{aligned}$$

$$p_{ij} = p_{ij} = s_j d_{ij} e_{ij}$$

x_{jg} = binary (1/0) decision variable (passive restoration) to allocate in decision unit j within Local Government Areas g

m_g = decision units within Local Government Areas g

c_{jg} = the opportunity cost in decision unit j within Local Government Areas g

T_g = budget constraints applied to each Local Government Area g , where 3,5,10,20,30,40,50% of the total opportunity cost is equally allocated across Local Government Areas

comparison, which ignored equality and equity (table 1).

In the ‘baseline’ strategy, the available budget could be used to select decision units anywhere in the Brigalow Belt (box 2). In the ‘sectors’ strategy

the budget was equally divided among each beneficiary sector. In the ‘sectors + disadvantage’ strategy, the budget is equally divided among each beneficiary sector, but investments were preferentially directed to areas of highest socioeconomic disadvantage. In

Table 1. Investment strategies to promote equality and equity in the distribution of flood protection in the Brigalow Belt bioregion. Each strategy constitutes a different way of constraining resources for restoration investment.

		Investment strategy		
		Baseline	Seeks equality	Seeks equity
A	Resource allocation at the Brigalow Belt scale (baseline)		Equal resource allocation among beneficiary sectors (sectors)	Equal resource allocation among beneficiary sectors, directed to areas of highest socioeconomic disadvantage (sectors + disadvantage)
B			Equal resource allocation per local government area (LGA)	Equal resource allocation per LGA, directed to areas of highest socioeconomic disadvantage (LGA + disadvantage)

the 'LGA' strategy, the budget was equally divided between 18 LGAs (6 were excluded as they did not have area available for intervention or infrastructure at risk, see table S1). In the 'LGA + disadvantage' strategy, the budget is equally divided among each LGA, but investments were preferentially directed to areas of highest socioeconomic disadvantage.

2.3. Comparing efficiency, equality, and equity among strategies

We compared changes in efficiency, equality and equity between the 'baseline' and the 'sectors' and 'sectors + disadvantage' strategies (table 1(A)); and between the 'baseline' and the 'LGA' and 'LGA + disadvantage' strategies (table 1(B)). We assessed efficiency as the total sum of flood protection benefits (across all decision units selected) at each budget level. We assessed equality using the Gini coefficient because it is a widely used measure of statistical concentration among values of a frequency distribution (Ceriani and Verme 2012). The Gini coefficient is applicable to any size distribution of general data sets, and has been globally used to assess social inequality (Sitthiyot and Holasut 2020). It has also been used to assess the distribution of ecosystem services at different spatial scales (Ceriani and Verme 2012, Li *et al* 2017, Benra and Nahuelhual 2019, Yang *et al* 2021). The Gini coefficient does not account for absolute distributions, but this is acceptable given that we use the Gini coefficient as a relative measure of change in the distribution of flood protection (Sitthiyot and Holasut 2020). We calculated the Gini coefficient using the 'gini' function from package REAT, version 3.0.2, R, where values of 0 mean perfect equality while values of 1 perfect inequality. To assess changes in equality among beneficiary sectors (table 1(A)) the Gini coefficient was calculated based on the sum of flood protection benefits for each beneficiary sector across decision units selected. To assess changes in equality among LGAs (table 1(B)) the Gini coefficient was calculated based on the sum of flood protection benefits for each LGA. Decision units differed in the amount of area available for intervention (table S1), to account for this, we weighted the Gini coefficient considering the total area available for intervention within decision units selected. We assessed equity by estimating the extent to which

areas of highest socioeconomic disadvantage were captured across all strategies using the Index of Relative Socio-Economic Disadvantage (IRSD) (ABS 2018). The IRSD reflects people's access to material and social resources and is based on variables such as income, education, employment, occupation and housing characteristics (ABS 2018). We use the IRSD as a proxy for people's capacity in the region to recover economically and psychologically from the damages of flood events (Morrissey and Reser 2007, Veitch 2009).

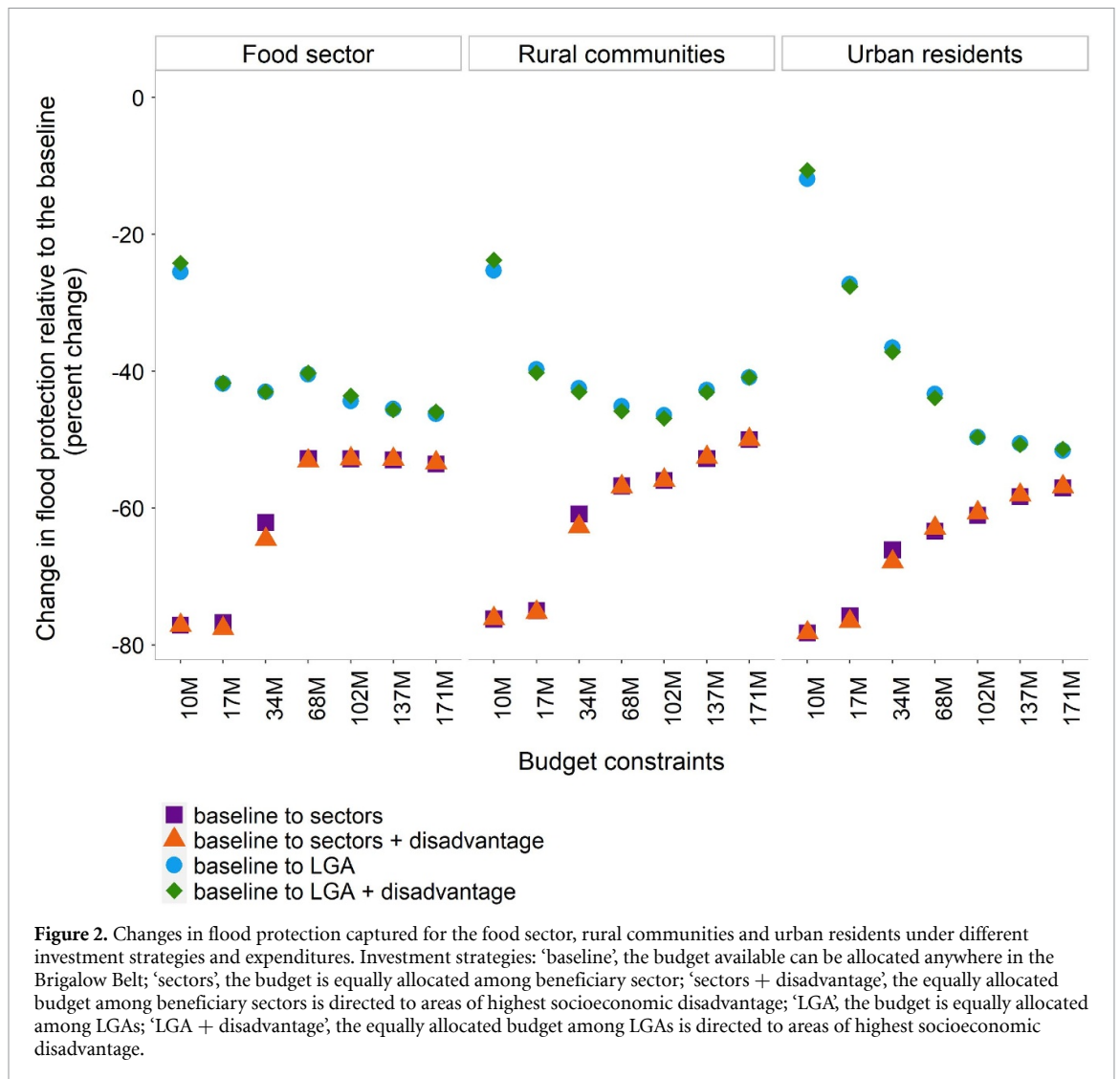
3. Results

3.1. Impacts on efficiency

All our investment strategies were less efficient at capturing flood protection for all beneficiary sectors than the 'baseline', where equality and equity were ignored. That is, under the same budget, any other strategy captured less flood protection than the 'baseline' (figure 2). The 'sectors' and 'sectors + disadvantage' strategies represented high losses in efficiency compared to the 'baseline' (figure 2). This is particularly true at the lowest budget levels. For example, at a \$10 M budget, the 'sectors' strategy captured almost 80% less flood protection for our three beneficiary sectors than the 'baseline' (figure 2). This is explained by an overall reduction in the number of decision units selected in favor of achieving the allocated expenditure per beneficiary sector. Both the 'LGA' and 'LGA + disadvantage' strategies implied a similar reduction in efficiency compared to the 'baseline' strategy. This was 25% for rural communities and the food sector, while 12% for urban residents at the \$10 M budget constraint, at higher expenditures reductions in efficiency reached ~50% (figure 2).

3.2. Impacts on equality among beneficiary sectors

The 'baseline' investment strategy resulted in highly disproportionate distributions of flood protection among beneficiary sectors (figure 3). That is, from the total amount of flood protection captured in the 'baseline' strategy at a \$10 M budget, the food sector received almost twice the protection than urban residents received, and around 14 times more than rural communities (figure 3(a)). The inequality in the distribution of flood protection among

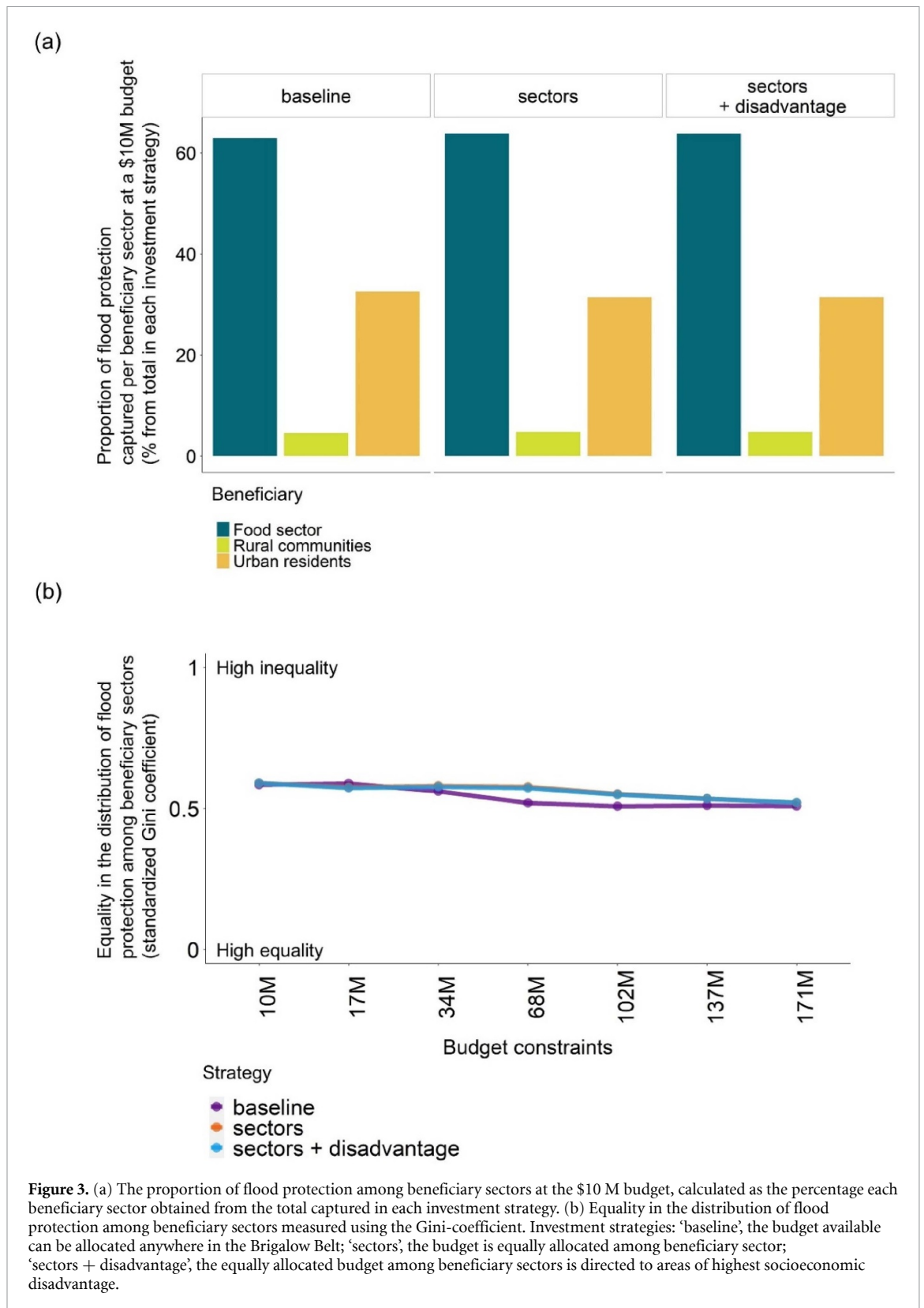


beneficiary sectors is also reflected in a Gini coefficient of ~ 0.6 obtained in the ‘baseline’ strategy (figure 3(b)). We found the ‘sectors’ strategy to be unsuccessful at improving equality among beneficiary sectors compared to the ‘baseline’ (figure 3). The proportion of flood protection captured from this strategy was very similar to the ‘baseline’, that is, highly inequitable and favoring the food sector (figure 3). Demand for the food sector was widely spread across the landscape, resulting in indirect benefits for this beneficiary sector even when it was not specifically targeted (Villarreal-Rosas *et al* 2022). On the other hand, demand by rural communities was more localized (Villarreal-Rosas *et al* 2022), resulting in a smaller proportion of benefit captured by this sector. This explains why the proportion of flood protection among beneficiaries is almost identical in the ‘baseline’, ‘sectors’ and ‘sectors + disadvantage’ strategies (figure 3).

3.3. Impacts on equality among LGAs

High inequality was found in the distribution of flood protection among LGAs in the ‘baseline’ strategy,

particularly at \$10 and \$17 M budget constraints, with Gini coefficients of 0.9 and 1 respectively (figure 4). We found the ‘LGA’ strategy to be successful at improving equality among LGAs compared to the ‘baseline’ strategy (figure 4). The highest improvement in equality among LGAs was at the \$17 M budget (5% of total), with Gini coefficients changing from 1.0 (perfect inequality) to <0.7 between the ‘baseline’ and ‘LGA’ strategy (figure 4). Under the ‘LGA’ strategy, inequality progressively increased as the budget increased and more area was selected (figure 4). This is explained by some LGAs having all decision units already selected, while others having additional units available for selection with higher budgets. Irrespective of the strategy, equality among LGAs converge to intermediate Gini coefficients as more area gets selected (as reflected in the \$137 and 171 M budget constraints) (figure 4). This suggests that, as more area is selected, the distribution of flood protection among beneficiary sectors is influenced more by the landscape interactions between supply and demand areas providing flood protection (as found in Villarreal-Rosas *et al*



2022) than the investment strategy. The high inequality found under the ‘baseline’ strategy is explained by four LGAs (Charters Towers, Livingstone, Blackall Tambo, Balonne) that did not receive any flood protection benefit at all under the ‘baseline’ strategy, while the ‘LGA’ strategy ensured some level of flood protection for all LGAs (figure 5).

3.4. Impacts on equity

The ‘baseline’ strategy captured areas of similar socioeconomic disadvantage for our three beneficiary sectors, with values ranging between 0.17 and 0.20, from a maximum of 0.30 (indicating higher disadvantage) (figure 6). The ‘sectors + disadvantage’ strategy captured areas of similar

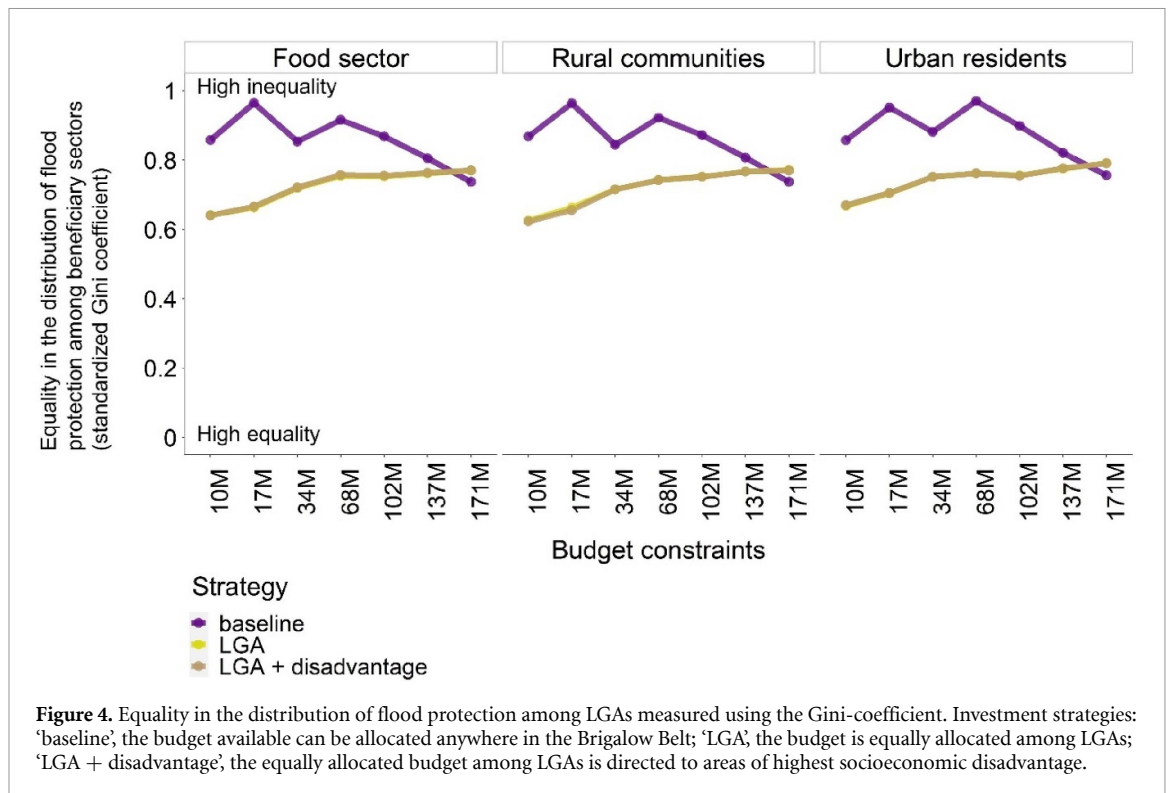


Figure 4. Equality in the distribution of flood protection among LGAs measured using the Gini-coefficient. Investment strategies: ‘baseline’, the budget available can be allocated anywhere in the Brigalow Belt; ‘LGA’, the budget is equally allocated among LGAs; ‘LGA + disadvantage’, the equally allocated budget among LGAs is directed to areas of highest socioeconomic disadvantage.

socioeconomic disadvantage values to the ‘baseline’ strategy (figure 6). This indicates that, our investment strategy seeking to improve equity among beneficiary sectors in the Brigalow Belt performs no better than strategies entirely ignoring socioeconomic disadvantage at the 10 M budget constraint (3%). The ‘LGA + disadvantage’ strategy captured areas of higher socioeconomic disadvantage values for rural communities and urban residents than the ‘baseline’ strategy at a \$10 M budget constraint (figure 6). Higher expenditures in the ‘LGA + disadvantage’ strategy do not improve equity compared to our other strategies (figure S1). As opposed to the ‘sectors + disadvantage’, the ‘LGA + disadvantage’ strategy was successful at capturing areas of highest disadvantage as it promoted the selection of decision units in each LGA that would otherwise not be selected. The disadvantage values captured for the food sector across all our different strategies did not change much due to a more homogeneous disadvantage index for this beneficiary sector across the Brigalow Belt (figure 6).

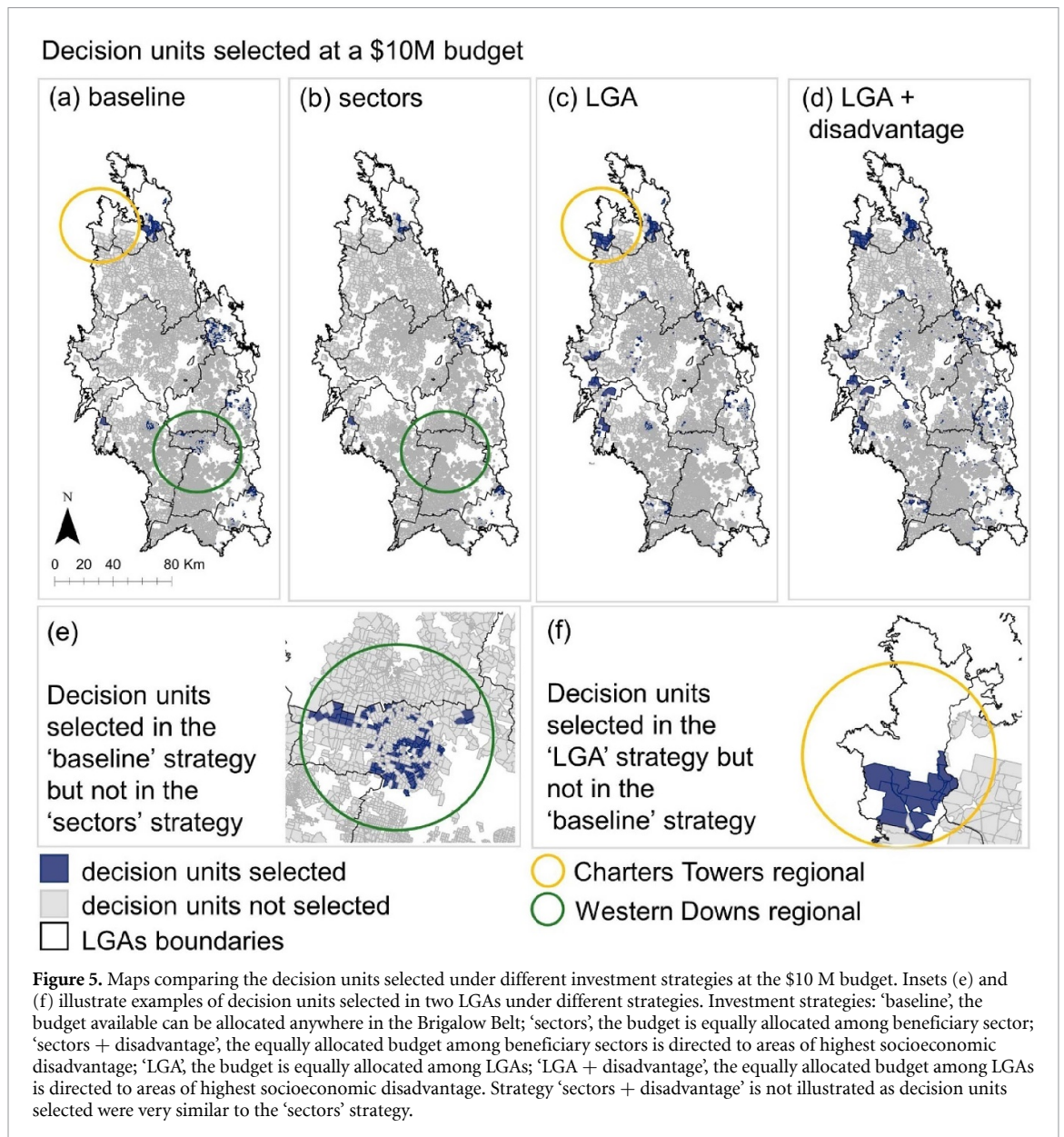
4. Discussion

We use a spatially explicit prioritization framework to identify how different investment strategies perform at improving equality and equity among beneficiary sectors and LGAs, and the extent to which efficiency is compromised as a result. Management plans incorporating multiple beneficiary sectors imply inherent trade-offs, and systematic prioritization approaches, like the one we apply here, are critical to making such compromises transparent (Halpern *et al* 2013,

Villarreal-Rosas *et al* 2020). Below we discuss the implications of promoting equality and equity when planning for ecosystem services and indicate aspects to consider in future work to help operationalize fair management plans.

4.1. Lessons learnt from our investment strategies

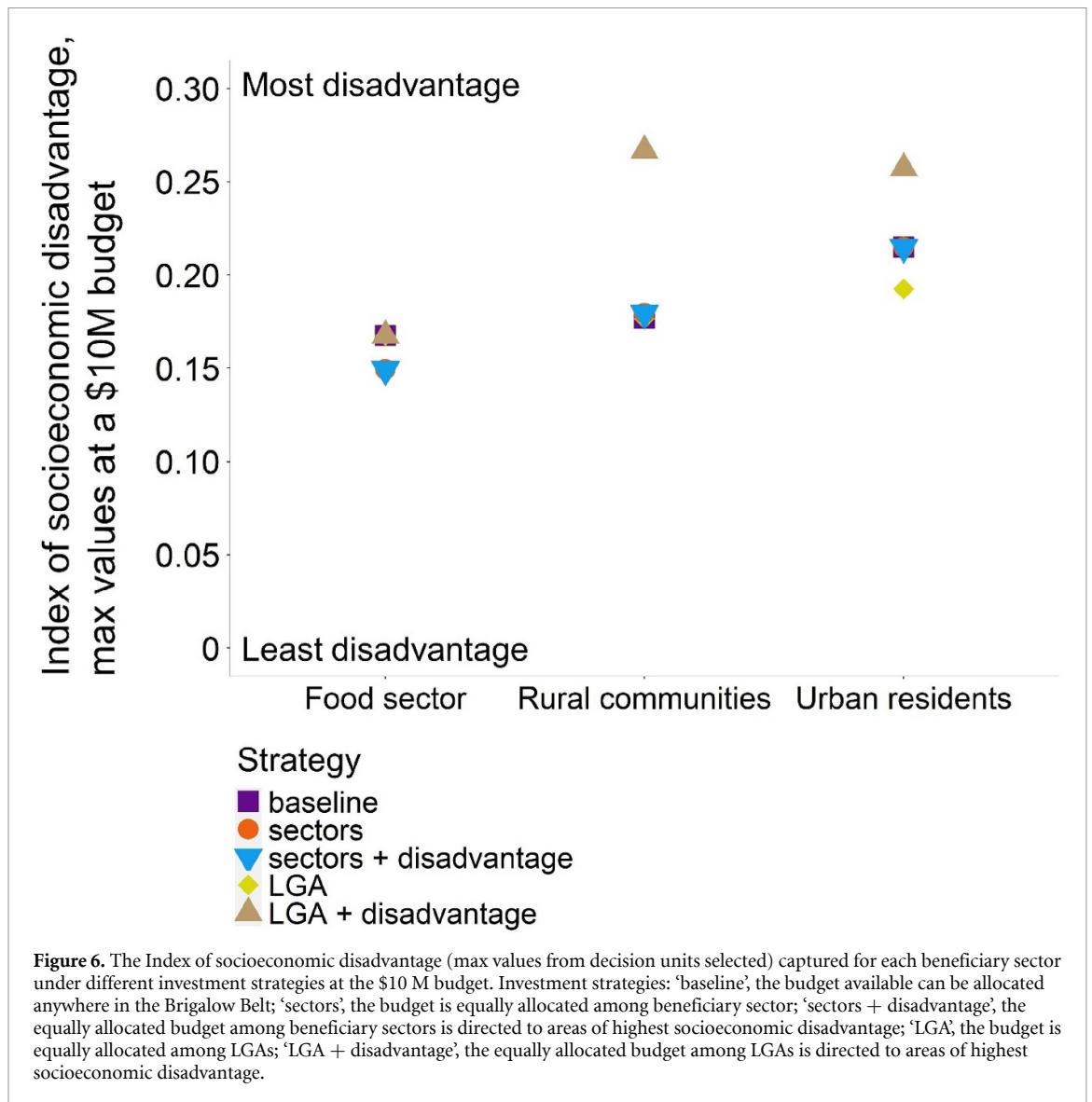
The ‘baseline’ strategy demonstrated that without consideration of equality or equity in the planning process, flood protection benefits of passive restoration are disproportionately distributed among beneficiary sectors and LGAs. Our investment strategies sought to improve equality and equity by changing how monetary resources available for intervention were allocated. The strategy ‘sectors’, aiming at improving equality among beneficiary sectors was unsuccessful; it resulted in large reductions in efficiency and did not improve equality among beneficiary sectors compared to the ‘baseline’. Inequalities in the distribution of flood protection among sectors in the context of forest restoration are explained by (a) the specific configuration of demand for the different beneficiary sectors in the Brigalow Belt and (b) the characteristics relevant to the provision of flood protection. Flood protection is considered a non-rival service, whereby the service does not degrade or transform when someone uses or benefits from it (Fisher *et al* 2009). In our approach, we assume flood protection is a perfectly non-rival service, which means that our decision units were not exclusive to beneficiary sectors, as flood protection provided to one beneficiary sector does not decrease protection to other beneficiary sectors. Given the wide distribution



of demand from the food sector, most decision units that were selected to benefit the urban or rural sector indirectly also benefited the food sector, resulting in unequal distributions of benefit. Applying our 'sectors' strategy to other ecosystem services and planning contexts may return very different results. For instance, provisioning ecosystem services like timber extraction are considered rival (i.e. another person cannot benefit from timber extraction if some else has already benefitted from it) (Fisher *et al* 2009). In this case, evenly distributing economic resources for reforestation could achieve equal gains in forest cover across different communities (Orsi *et al* 2011), although people's capacity to obtain profit from timber extraction may differ (Chomba *et al* 2016).

The strategy 'LGA' aimed at improving equality among LGAs was successful; although it represented

an increase in costs of up to 25%, it ensured flood protection to all LGAs, including four that would be missed otherwise. This is important because solutions that miss benefit for some locations are less likely to be accepted and implemented successfully (Halpern *et al* 2013, Klein *et al* 2015, Kovacs *et al* 2016, Ali *et al* 2020). Thus, potential efficiency losses of enhancing equality may be minor if we assume that solutions that ignore equality have a lower probability of implementation success (Halpern *et al* 2013, Rosenthal *et al* 2015). In addition, our results show that equality and equity among LGAs does not improve beyond the \$10 M budget constraint. Hence, identifying the optimal expenditure required to enhance equality or equity, as we do in this study, can help avoid unnecessary investments. Ensuring benefit is distributed among the different beneficiaries and locations where it is demanded is a policy imperative



(Chan and Satterfield 2020, Mandle *et al* 2020), and our approach provides a way for practitioners and policy makers to identify efficient solutions that benefit all beneficiaries and locations across a landscape.

There is an ethical imperative in spatial conservation planning for ecosystem services to ensure positive outcomes for the most vulnerable sectors of the population (Daw *et al* 2011, McDermott *et al* 2013, Althor *et al* 2016). In order to address this, we accounted for socioeconomic disadvantage in our investment strategies. That is, we sought to improve equity in our solutions by directing flood protection to areas with less opportunity to overcome damages of flood events. We expected to see a contrasting difference in the decision units selected and higher allocations to socially disadvantaged locations when specifically targeting disadvantage (i.e. 'sectors' vs 'sectors + disadvantage' and 'LGA' vs 'LGA + disadvantage'). However, this was not the case given the narrow range of the socioeconomic

disadvantage index in the region ($>0-0.3$) and a moderate correlation between areas of high demand of flood protection and high disadvantage across the Brigalow Belt (table S2). That is, prioritizing flood protection to areas with high demand (our overarching conservation objective) already captured areas of high disadvantage. Similar results were found in Gourevitch *et al* (2020), where the economic value of houses subject to flooding was quite homogeneous. Therefore, targeting equity-weighted utility of flood risk reduction only represented small changes in area selection compared to not targeting equity-weighted utility (Gourevitch *et al* 2020). We suspect more contrasting differences between ignoring and accounting for disadvantage may occur in regions where socioeconomic differences across the population are marked (Pedlowski *et al* 2002, Suwarno *et al* 2016, Abebe *et al* 2020).

Despite the narrow changes in decision units selected when targeting disadvantage, our results indicate that investment strategies may require to

be specific to a beneficiary sector. For instance, accounting for disadvantage for the food sector may not be necessary as doing so costed more for no equity benefit. This is because demand for flood protection for the food sector was located across highly homogenous socioeconomic areas. Conversely, accounting for disadvantage represented relevant improvements in equity for urban residents and rural communities. Thus, the food sector could be treated separately in the planning process to increase overall efficiency. Other locations of even higher socioeconomic disadvantage for urban residents and rural communities (e.g. Townsville City, the top North LGA, see figure 6) were not captured as no units to apply passive restoration were available that would deliver protection to them (based on the supply-demand configurations for each beneficiary sector at the sub-watershed level). Alternative management interventions may be necessary to enhance protection against flood events for those regions. Possible alternatives targeting the demand component include improved zoning regulations, property relocation, or improving emergency responses from people (Gourevitch *et al* 2020, Villarreal-Rosas *et al* 2020).

4.2. Operationalizing fair management plans

What is regarded as a fair distribution of ecosystem service benefits depends on the sociocultural and economic circumstances that affect beneficiaries in a planning region (McDermott *et al* 2013, Vucetich *et al* 2018). Our study highlighted the winners, losers, and costs of alternative strategies promoting equality and equity in the distribution of flood protection in the Brigalow Belt Bioregion. Negotiations would then be required to identify what solutions are acceptable for all beneficiaries, even if that involves unequal distribution of benefits (Vira *et al* 2012, Kovacs *et al* 2016). Alternative strategies are available to balance trade-offs among beneficiary sectors (Fu *et al* 2018, Wang *et al* 2020). For instance, in compensatory programs, one beneficiary sector provides economic compensation to other sectors in return for applying actions that enhance ecosystem services (Bremer *et al* 2018, Wang *et al* 2020). For example, in the Yongding River watershed in China, a fair cost-sharing program for maintaining water quality required downstream beneficiaries in Beijing pay US\$6.31 M to upstream provinces (Fu *et al* 2018). Previous research in the Brigalow Belt has shown the economic feasibility of compensating farmers in return of carbon sequestration (Evans *et al* 2015). Flood protection services could also be included as part of a Payments for Ecosystem Services scheme, where some of the funds are directed to ensure benefit to rural communities (the beneficiary sector obtaining least flood protection benefit from intervention). Exploring how compensatory schemes could be applied to address disproportionate

distribution of flood protection within beneficiary sectors for the Brigalow Belt was beyond the scope of this study. Yet, we provide baseline information to expand on this analysis describing how benefits are distributed across the landscape for different beneficiaries.

Advancing towards fair outcomes in spatial prioritization for ecosystem services requires early engagement with beneficiary sectors and recognition of their socio-cultural and political context (Vira *et al* 2012, Rosenthal *et al* 2015, Kovacs *et al* 2016). For example, in North India, monetary compensations for upstream beneficiaries to protect and sustainably manage forested areas were provided by downstream beneficiaries in return of better water quality and increased protection against flood events (Kovacs *et al* 2016). However, imbalanced power relations between the rural upstream and wealthier downstream towns created intra-community conflicts in the upstream town, undermining their capacity to build collective institutions fundamental for the long-term existence of the compensatory schemes (Kovacs *et al* 2016). These examples indicate the need to explore beyond how benefits are spread in society (as we do in this study) to also consider the underlying socioeconomic conditions that influence the ability of sectors to derive ecosystem services (McDermott *et al* 2013). For instance, people may have physical access and desired demand for particular ecosystem services, but lack the power or capabilities for deriving benefit (Daw *et al* 2011, Vira *et al* 2012, Hanna *et al* 2020). In our approach, we assessed flood protection at the watershed level, and we then aggregated results at the LGA scale. This was useful to represent areas at which many decisions regarding water management take place in the Brigalow Belt (State of Queensland 2020). Yet, watershed boundaries at which flood protection services are produced and delivered usually expand beyond the limits of LGAs. Thus, future compensatory plans for the Brigalow Belt should consider the degree of collaboration across LGAs and other government levels, as well as an assessment of the power dynamics and hierarchies between beneficiary sectors in the region.

Also of high priority in future studies is to incorporate temporal dynamics affecting distributional outcomes. In our approach, we assume demand and disadvantage factors are static. However, this is unlikely, and accounting for the temporal variability of these factors may drastically affect the distribution of ecosystem services among beneficiaries (Villarreal-Rosas *et al* 2020). Thus, promoting and assessing fairness in conservation plans also requires comparison of the expected changes in ecosystem service distribution across time, together with an assessment of the changes in the socioeconomic opportunities different people experience.

5. Concluding remarks

Achieving efficient and fair outcomes from management and conservation interventions targeting ecosystem services is a desirable goal pursued by practitioners and decision-makers, but it involves trade-offs. Here we have identified the type and extent of trade-offs between efficient, equal, and equitable solutions under a spatially explicit prioritization framework. In the Brigalow Belt, even budget allocations are a poor strategy to promote equal and equitable distributions of flood protection among beneficiaries, but successful at promoting equality and equity among LGAs. These findings were largely determined by the configuration of demand, and patterns of socioeconomic disadvantage specific to the beneficiary sectors we considered. Trade-offs between equity, equality, and efficiency from the application of similar investment strategies are likely to vary depending on the specific ecosystem services, beneficiaries, and planning contexts. Recognition of the potential trade-offs between different beneficiaries caused by management interventions is critical to identify solutions that beneficiaries regard as fair and sustainable.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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Conflict of interest

The authors have no conflicts of interest to declare.

CRedit authorship contribution statement

Jaramar Villarreal-Rosas: conceptualization, methodology, software, validation, formal analysis, investigation, resources, writing—original draft, visualization. Adrian L Vogl: methodology, software, validation, resources, writing—review and editing. Laura J Sonter: writing—review and editing, supervision. Hugh P Possingham: conceptualization, writing—review and editing, supervision. Jonathan R

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