https://doi.org/10.1002/aqc.2891

Catchment zoning to enhance co-benefits and minimise trade-offs between ecosystem services and freshwater biodiversity conservation.

Virgilio Hermoso[1,2], Lorenzo Cattarino[2], Simon Linke[2] and Mark J. Kennard[3]

[1] Centre Tecnològic Forestal de Catalunya. Crta. Sant Llorenc de Morunys, Km 2, 25280, Solsona. Lleida, Spain.

[2] Australian Rivers Institute, Griffith University, Nathan, Queensland, 4111, Australia.

[3] Australian Rivers Institute and National Environmental Science Program Northern Australia Environmental Resources Hub, Griffith University, Nathan, Queensland, 4111, Australia.

Running head: Planning for biodiversity and ecosystem services.

Corresponding author:

Virgilio Hermoso.

Centre Tecnològic Forestal de Catalunya. Crta. Sant Llorenc de Morunys, Km 2, 25280, Solsona. Lleida, Spain.

Email: virgilio.hermoso@gmail.com

Ph.: (+34) 973 481752

Abstract

1. Integrating ecosystem services (ESS) in landscape planning can help identify conservation opportunities by identifying co-benefits between biodiversity conservation and maintenance of regulating and cultural ecosystem services. However, the adequate integration of ESS needs careful consideration of potential trade-offs specially between provisioning services and biodiversity conservation (e.g., the potentially negative consequences of agricultural water extraction within areas important for maintenance of biodiversity). These trade-offs have been overlooked in systematic spatial planning to date, especially in freshwater systems.

2. The software Marxan with Zones was used to identify priority areas for conservation of freshwater biodiversity (139 species of freshwater fish, turtles and waterbirds) and provision of freshwater ESS in the Daly River, northern Australia. Four different surrogates for ESS were mapped including those potentially incompatible with conservation goals (i.e. groundwater provision for agriculture, recreational fisheries) and those that are more compatible with conservation (i.e. flood regulation by riparian forests, and provision of perennial water). The spatial allocation of multiple management zones was prioritised: (1) three conservation zones aiming to represent freshwater biodiversity and compatible ESS to enhance co-benefits and (2) two production zones, where access to provisioning ESS could be granted. The representation of ESS obtained when using the multi-zoning approach was compared with that achieved with a single management zone approach. The comparison was done across different representation targets.

3. Different results were found at low and high targets for ESS. At low targets (<25% of all ESS), the multi-zoning approach achieved up to 53% more co-benefits than the single zone approach. At high targets (>25% of all ESS), trade-offs avoided were more evident with up to 56% less representation of incompatible ESS within conservation zones.

4. Multi-zone planning could help decision-makers better respond to the increasingly complex catchment management context due to increasing demand for provisioning services and

diminishing availability of resources, as well as management and planning challenges in other realms facing similar problems.

Keywords: freshwater, flood regulation, agriculture suitability, management zones, Marxan with Zones, perennial water, recreational fisheries.

Introduction

Ecosystem services (ESS) are increasingly recognised for their importance to human wellbeing but are threatened by unsustainable use and environmental degradation (van Jaarsveld et al., 2005; Carpenter et al., 2009). There is an urgent need to integrate ESS into local and regional landscape planning (Martinez-Harms et al., 2015; Mitchell et al., 2015¸ Tallis, & Polasky, 2009) to ensure their adequate protection and maintenance in the long term, and safeguard human wellbeing (Balvanera et al., 2001; Ormerod, 2014). The consideration of both ESS and biodiversity in decision-making can advance more holistic landscape management and create new opportunities for sustainable use of ecosystems and biodiversity conservation (Egoh et al., 2007; Mitchell et al., 2015; Schröter et al., 2014.

However, simultaneous prioritisation and management of multiple ESS and biodiversity is challenging as securing access to some services might threaten other services (Acreman et al., 2011; Sanon, Hein, Douven, & Winkler, 2012) or biodiversity directly (Adams, Alvarez-Romero, & Pressey, 2016; Martínez-Harms et al., 2015; Morán-Ordoñez et al., 2017). For example, granting access to an ecosystem service like water provision in a given area might compromise the delivery of other related services such as recreational uses, and ultimately the persistence of biodiversity (Dudgeon, 2014). Such trade-offs should be explicitly considered when planning for provisioning services (Howe, Suich, Vira, & Mace, 2014; Luck, Chan, & Fay, 2009; Schröter et al., 2014; Tallis, Kareiva, Marvier, & Chang, 2008). On the other hand, there are opportunities to enhance co-benefits between biodiversity and the maintenance of ESS that are more compatible with biodiversity conservation (Atkinson et al., 2016). This is the case, for example, for some regulating services such as carbon storage/sequestration and for cultural services such as aesthetic/ recreational value of ecosystems that can also enhance conservation of biodiversity (Bryan et al., 2015; Venter, Hovani, Bode, & Possingham, 2013).

Achieving win-win situations, where both development and conservation coexist, needs explicit consideration of trade-offs and co-benefits between biodiversity conservation and ESS protection. However, most efforts to date have been directed towards exploring co-occurrence patterns between different ESS and biodiversity (Martínez-Harms et al., 2015) with contrasting results (e.g. Chan, Shaw, Cameron, Underwood, & Daily, 2006; Egoh et al., 2010; Naidoo et al., 2008). For this reason, further efforts are needed to make trade-offs explicit in spatial prioritization and help address sustainability challenges (Goldstein et al., 2012). These studies are particularly needed in freshwater systems because freshwater-derived ESS are critically important for human wellbeing but are increasingly threatened (e.g., water provision; Vörösmarty et al., 2010), and ii) these systems have received little research and management attention to date (Boulton, Ekebom, & Gíslason, 2016; Martínez-Harms et al., 2015).

Here a novel approach to explicitly address trade-offs and co-benefits between freshwater ESS and biodiversity conservation in spatial conservation prioritisation is demonstrated, using the Daly River catchment in northern Australia as an example. Four different ESS were mapped including those potentially incompatible with conservation goals (i.e. groundwater provision for agriculture, recreational fisheries) and those that are more compatible with conservation (i.e. flood regulation by riparian forests, and provision of perennial water). The software Marxan with Zones was used to simultaneously identify priority areas for conservation of freshwater biodiversity (139 species of freshwater fish, turtles and waterbirds) and provision of ESS while maximising co-benefits between biodiversity conservation and compatible ESS and minimising potential trade-offs with incompatible ESS (Fig. 1). This approach and recommendations enable better integration of ESS and biodiversity conservation in landscape planning by harmonising development and conservation towards more sustainable alternatives, and fills a critical gap in current planning approaches.

Methods

Study area and spatial framework

The Daly River catchment in northern Australia (53,000 km^2) has important ecological, cultural and economic values and is in relatively good environmental condition compared with most other large Australian river catchments. However, the catchment is under considerable pressure for further groundwater use and agricultural developments that pose considerable threats to these values (Adams et al., 2014; Chan et al., 2012). A total of 865 subcatchments were derived from a 9 s digital elevation model (Hutchinson, Stein, Stein, Anderson, & Tickle, 2008) in ArcGIS 10.1 (ESRI, 2011) to use as planning units for the analysis. Each subcatchment included the portion of river length between two consecutive nodes or river connections (8.0 km on average) and its contributing area (66.1 km^2 on average), representing an appropriate grain size of planning units for freshwater conservation planning (Hermoso, & Kennard, 2012).

Biodiversity data

The spatial distribution of 45 freshwater fish species, 8 turtle species and 86 waterbird species (Appendix S1) was used as biodiversity surrogates in the analysis and were sourced from Kennard (2010). Complete coverage of species distributions was derived from multivariate adaptive regression splines models (Leathwick, Rowe, Richardson, Elith, & Hastie, 2005) built on a data set of 1328 sampling sites for fish, 2109 sampling sites for waterbirds and 350 sites for turtles (see Hermoso, Kennard, & Linke, 2012 for more details on predictive models) representing the most comprehensive dataset on distribution of freshwater biodiversity for the region (Kennard, 2010).

Mapping surrogates for ecosystem services

Different surrogates for mapping the distribution of four different ESS (following the Classification of Ecosystem Services proposed by Maes et al., 2014) were used in the Daly River catchment, namely agriculture suitability, recreational fisheries, carbon storage/ flood retention, and presence of perennial water bodies. In some cases, the surrogate used here are measures of the ecosystem structure that supports the service (e.g., perennial water or agriculture suitability), but were taken as the best surrogate available in the study area. These were selected to cover three main types of ESS: provisioning (e.g., agriculture suitability), cultural (e.g., recreational fisheries and presence of perennial water bodies for aboriginal communities) and regulating (e.g., carbon storage/ flood retention) (Millennium Ecosystem Assessment, 2005) and represent the potential the catchment can offer rather than the released or extracted amount for each service. The representative range of ESS also demonstrates the two types of situations aimed in this study: potential co-benefits between securing the persistence of compatible ESS, such as regulating services, and biodiversity conservation and trade-offs between provisioning ESS and biodiversity conservation/ other ESS.

i) Agriculture suitability

Northern Australia has been identified as a potential area for future agricultural development, for which groundwater provision will be essential (Morán-Ordoñez et al., 2017; Webster et al., 2009). Estimates of agricultural suitability were used as a surrogate for potential demand of groundwater provision. This was considered an appropriate surrogate as the major water supply for agriculture in the Daly River catchment is from groundwater extraction (Chan et al., 2012). Spatial variation in agriculture suitability (Fig. 2b) was sourced from Pascoe-Bell et al., (2014) and integrates information on soils, landforms and groundwater resources and their suitability for different types of agriculture and pastoral uses. Here, only the types of agriculture that require water provisioning (i.e. irrigated cropping and perennial horticulture) were selected, as trade-offs with biodiversity conservation arise from the potential negative effect that the exploitation of aquifers might have on surface freshwater ecosystems (e.g., decreasing flows and water availability during dry periods; King, Townsend, Douglas, & Kennard, 2015). The total area within each subcatchment suitable for irrigated crops and perennial horticulture was summed and used it as a surrogate for the potential water demand derived from the agricultural development of the subcatchment.

ii) Recreational fisheries

The most popular freshwater fish species for recreational fishing in the region was selected for mapping areas of potential value for this service (Fig. 2c). The spatial distribution of barramundi (*Lates calcarifer*) derived from predictive models described above (Kennard, 2010) was filtered by accessibility to recreational fishing (see Close et al., 2014). In this way, only areas of potential distribution for barramundi that were accessible from road (5-km buffer along roads) or close to regional towns (e.g., Katherine and Pine Creek; 25-km buffer around towns) were considered. In this way, recreational fishing was assumed to have the potential to impact populations of barramundi and other freshwater species and then included this service in the list of potential trade-offs for further analyses.

iii) Carbon storage/ Flood regulation

The spatial extent of the riparian forest, sourced from the National Vegetation Information System (NVIS; Australian Government Department of the Environment, 2012) was used as a surrogate for the service this type of vegetation offers for carbon storage and flood regulation (Fig. 2d; Tockner, & Stanford, 2002). The total area covered by riparian forest within a 250-m buffer along rivers and streams was measured for each subcatchment, where clearing is prohibited (Adams, & Pressey, 2014) and where the service could be secured. NVIS provides spatially explicit data on vegetation cover, from which only trees and shrubs classes were considered suitable for providing the service. The service was then assumed to be proportional to the area covered by riparian forest in each subcatchment. It was also assumed that by maintaining riparian vegetation, and the ESS provided by it, would bring co-benefits to biodiversity conservation. For example, riparian vegetation provides habitat for freshwater and terrestrial biodiversity, contributes to maintenance of trophic webs and provides shade that helps regulate water temperature (Pusey, & Arthington, 2003).

iv) Perennial water

Perennial water bodies offer services to local communities as they are an important source of resources (e.g., food and building materials) especially during the dry season (Jackson, Finn, & Featherston, 2012). The area within each subcatchment covered by perennial palustrine, lacustrine and riverine water bodies was measured (Fig. 2e). The extent of these water bodies was sourced from Geoscience Australia (2006) and summarised at the subcatchment scale. It was assumed that by maintaining this service it could be possible to bring co-benefits to biodiversity conservation, as they offer key refugia to freshwater species during recurrent dry periods (Hermoso, Ward, & Kennard, 2013) and access to water to support terrestrial biodiversity (Woinarski, Mackey, Nix, & Traill, 2007).

Definition of management zones

The software Marxan with Zones (Watts et al., 2009) was used for producing a catchment plan where the allocation and extent of different management zones can be prioritized simultaneously to address trade-offs and co-benefits between ESS and biodiversity conservation (Fig. 1). Marxan with Zones uses a simulated annealing optimisation algorithm to minimise an objective function similar to Marxan (Ball, Possingham, & Watts, 2009). The objective function in Marxan is composed of three different parameters: i) the cost associated to the management of all planning units in the solution, ii) penalties for not achieving targets for all conservation features, and iii) connectivity penalties for missing connections, along the river network in this case (Hermoso, Linke, Possingham, & Prenda, 2011). In this way the overall cost of representing all conservation features in a connected network of priority areas was minimised. The objective function used in Marxan with Zones is slightly more complex as there is more than one management zone (see Watts et al., 2009 for further detail on the mathematical formulation of Marxan with Zones) and so there are penalties for missed targets for each zone or connectivity both within and across zones. The longitudinal component of connectivity that was addressed here is critical to maintaining ecological processes like longitudinal migrations or the transfer of energy along river networks. However, connectivity in freshwater systems extends to additional lateral, vertical and temporal components that have not been incorporated in this study for the sake of simplicity but that could be relevant to some of the taxa included in the analyses such as water birds [see Hermoso, Kennard, & Linke (2012) and Hermoso, Ward, & Kennard (2012) for a demonstration on how to incorporate additional components of freshwater connectivity in Marxan].

The management plan included five different zones, three with conservation purposes and two additional ones to address trade-offs between incompatible ESS and biodiversity conservation and maintenance of compatible ESS (*production zones*; Fig. 1). The three conservation zones were designed to address special conservation needs in freshwater ecosystems, following suggestions by Abell, Allan, & Lehner (2007). They proposed a multi-zoning hierarchy to help fulfil the spatial needs of freshwater conservation, such as longitudinal connectivity along streams, and ensure effective protection in a flexible way: (i) 'freshwater focal zones', which are key areas for the protection of freshwater biodiversity; (ii) 'critical management zones', that aim to ensure connectivity among freshwater focal zones and maintain their ecological functionality (e.g. allowing seasonal migrations); and (iii) 'catchment management zones' that link the entire upstream catchment to freshwater focal zones to ensure that land uses in the contributing catchments to freshwater focal zones do not compromise the persistence of the biodiversity and/ or ESS that are aimed to be protected (Fig. 1). On the other hand, incompatible ESS with conservation are represented within the trade-off zone. The two production zones were designed for representing incompatible ESS separately, addressing in this way also the potential negative relationship between water extraction and maintenance of freshwater fisheries.

Identifying priority areas to enhance co-benefits and minimise trade-offs

Two alternative features in Marxan with Zones were used for minimising potential trade-offs and enhancing co-benefits by specifying a) in which zones the representation targets (see below) for biodiversity and different ESS could be achieved, and b) how the different management zones should be spatially arranged (e.g., minimising potential impacts of trade-off zones on conservation zones).

a) Contribution to representation targets

The zone target file in Marxan with Zones (Watts, Steinback, & Klein, 2008) was used for specifying how much each zone can contribute to achieving the targets for biodiversity and

ESS. This can help minimise trade-offs by securing the achievement of targets for incompatible ESS (e.g., groundwater extraction for agriculture) only within the production zone designed for that. Zone targets can also be used to enhance co-benefits by allowing achievement of conservation targets and representation of ESS compatible with conservation in the same zone. With this aim, the achievement of conservation targets for species was mainly centred in freshwater focal areas, while critical and catchment management zones and catchment management zones would mainly contribute to supporting these core areas (e.g., securing connectivity or minimising propagation of upstream threats into core conservation areas; Hermoso, Cattarino, Kennard, Watts, & Linke, 2015) and representing ESS compatible with conservation. For this demonstration exercise the representation target for these ESS was split evenly across the three conservation management zones (e.g., one third in each). In order to minimise potential trade-offs, targets for agriculture suitability and recreational fisheries (incompatible ESS) could only be achieved within the production zones designed for granting access to them.

This spatial framework was used for trying to represent a minimum area of 200 km^2 for each of the 139 species´ distribution and six different targets for all ESS (5, 10, 25, 35, 50, and 75% of the total amount of each ESS). The species targets represent the entire distribution range of the 15 rarest species in the catchment and >25% of the distribution range for another 25 species. Under the lack of ecological knowledge to inform target setting, the target used here ensure adequate representation of the rarest species while avoiding over-representing the most common ones. These targets were set for demonstration purposes only and further research would be needed to i) ensure they are ecologically sound for species conservation and/ or ii) represent real demands and needs of ESS in the Daly River catchment. These increasing targets for ESS were used to explore the potential conflicts that may arise between conservation and exploitation of incompatible ESS in the catchment. A high Species Penalty Factor (SPF=10) was used to ensure full achievement of targets. High SPFs ensure that Marxan with Zones achieves targets for all features (species and ESS). Subcatchment´s area was used as surrogate for cost of each planning unit to account for the differences in size of planning units that differ from equal size units used in marine or terrestrial planning. This was necessary to avoid Marxan with Zones focusing the selection of large planning units mainly that could also provide with larger contribution towards the achievement of targets. To minimise the total area to be managed for the different purposes, minimising indirectly potential management and opportunity costs, the area of each subcatchment was used as a surrogate for cost (Ban, & Klein 2009). Alternative surrogates for cost commonly used include estimates of human disturbance or river integrity (e.g., Linke et al., 2012). In these cases, it is assumed that highly degraded areas would be less suitable for conservation purposes and then should be avoided form the solution. In this study, given the low intensity of human impact on the Daly River catchment compared to other major rivers in Australia, only area was used as the surrogate for cost. A constant Connectivity Strength Modifier (CSM=2.5) was used across all analyses. The CSM is a weight to the connectivity parameter within the objective function in Marxan with Zones and it ensures that management zones are connected along the river network (Hermoso et al., 2015).

b) Spatial arrangement of management zones

The boundary zone and zone target files (Watts et al., 2008) were used to guide Marxan with Zones on how the different zones should be spatially arranged and where conservation targets could be achieved depending on the main purpose of each zone respectively in a spatial arrangement similar to Hermoso et al. (2015). Then this approach identified a minimum set of freshwater focal areas that were connected by critical management zones and buffered upstream by catchment management zones (see also Abell et al., 2007 for conceptual details). In order to reduce the impact of production zones on priority areas for conservation and between each other (e.g., impacts of groundwater extraction for agriculture in those areas identified as highly suitable for freshwater biodiversity and fisheries), it was also sought to maximise the disconnection between the production zone designed for granting development of agriculture and the conservation zones and the freshwater fisheries zone.

The amount of compatible ESS (proportion of the total available at the catchment scale) represented within the three conservation zones were measured as an indicator of potential co-benefits between biodiversity conservation and ESS achieved (e.g., flood retention that would be protected under this management zone). The amount of incidental representation of incompatible ESS within conservation zones were also measured as an estimate of how much of these ESS would be compromised by conservation. The same analyses were repeated within the production zones. In this case the amount of incidental representation of compatible ESS indicates how much of these ESS would not be protected, while the amount of incompatible ESS indicates the trade-off achieved (e.g., how much water extraction for irrigation could be granted outside protected areas).

Marxan with Zones was run 100 times for all different Scenarios (5 million iterations each) and kept the best solution over all runs for subsequent analyses. The best solution was the solution with the lowest score for the objective function across all 100 runs. All estimates were compared against 100 random allocations of the same number of subcatchments per management zone for each management target to test whether the ESS were allocated across zones better than random.

To further characterise potential co-benefits and trade-offs achieved with the multi-zoning approach, priority areas for the achievement of all targets (biodiversity and ESS) in a single management zone were also identified by using Marxan (Ball et al., 2009). The same planning parameters were used (SPF, SCM and cost) as in previous analyses and ran Marxan 100 times (1.5 million iterations each). The amount of each ecosystem service within the best solution was used it as a benchmark to assessing the improvement in co-benefits and/or trade-offs achieved by using the multi-zoning approach. Higher co-benefits and lower trade-offs would be expected when using the multi-zoning approach than when using more traditional approaches like the single management zone in Marxan.

Results

All targets for biodiversity and ESS were achieved in the solutions for most target levels (Table 1). The only exception was the target unmet for the incompatible ESS under the 75% target scenario, in which case only 80% and 50 % of that target was achieved (Agriculture suitability and recreational fisheries respectively; Table 1).

The multi-zoning approach showed to be useful to improve co-benefits, achieving up to 54% and 53% higher representation of compatible ESS (perennial water and flood regulation respectively) within the three conservation zones than under the single management zone approach (Fig. 3 a,b). There was a high potential for conflict between conservation and exploitation goals in the catchment, as showed by the high incidental representation of incompatible ESS within the three conservation zones (Fig. 3 c,d). However, the multi-zoning approach also helped reduce potential trade-offs, especially at higher targets, when more conflict between conservation and exploitation of resources might happen. The representation of incompatible ESS within the three conservation zones was up to 56% and 52% (agriculture suitability and recreational fisheries respectively) lower than when using the single management approach in Marxan (Fig. 3 c,d).

The agriculture suitability zone was located in the upper catchment of the Daly River (Fig. 4), while some smaller tributaries in the middle catchment were chosen for recreational fisheries. Freshwater focal zones were distributed throughout much of the catchment to cover the spatial distribution and diversity of species used in the analyses. As sought by the optimization of the spatial allocation of the different zones, critical management zones were mainly connecting freshwater focal zones and catchment management zones buffered upstream freshwater focal areas, especially areas of the catchment allocated to trade-off zones (Fig. 4).

Discussion

This study demonstrates how a multi-zoning approach can be used to integrate ESS and biodiversity for catchment planning in freshwater ecosystems. This approach explicitly accounts for potential trade-offs, and maximises opportunities for co-benefits, between ESS and biodiversity. In order to enhance win-win situations, where human development and biodiversity conservation coexist, trade-offs were explicitly integrated in the planning process by including a management zone specifically designed for this purpose. By doing this, an approach that not only minimises trade-offs, but also minimises potential ESS losses derived from incompatibilities between conservation and exploitation of potential provisioning services has been demonstrated (e.g., groundwater extraction for agriculture or recreational fisheries). This should help enhance conservation practise by reducing conflicts from avoided trade-offs and creating new conservation opportunities from realised co-benefits. ESS were treated as additional management features to be represented in the solutions as normally done with species or biodiversity surrogates in conservation assessments. Given the capacity of Marxan with Zones to deal with larger number of features, the approach presented here could be applied to other cases where more species and/ or ESS were involved.

A multi-zoning approach where trade-offs are explicitly addressed can help better harmonise the exploitation of provisioning ESS and maintenance of other regulating/ cultural ESS and biodiversity at the catchment scale. To do so, two production zones were integrated in a multi-zone conservation approach (Hermoso et al., 2015) where provisioning services could be realised (e.g., agriculture suitability or recreational fisheries), while minimising the impact on important areas for conservation of biodiversity and compatible ESS. By explicitly considering these production zones in the prioritisation process, Marxan with Zones avoided the selection of areas with high potential for provisioning services in the areas for conservation purposes whenever possible, where extractive uses would need to be restricted. The production zones helped avoid potential conflicts between extraction of provisioning ESS and conservation of biodiversity and other regulating/ cultural services, given that the demand targets for these ESS were in most of cases achieved within this zone. These production zones could not secure, however, full achievement of targets for incompatible ESS when set over 75%. In this case, the exploitation of groundwater for agriculture and recreational fisheries could not be secured without conflict with the maintenance of flood regulation and perennial water and the representation of biodiversity in conservation zones. This demonstrates unavoidable trade-offs between these incompatible ESS and conservation when trying to secure access to a very large proportion of the ESS (see also Adams et al., 2016; Moran-Ordoñez et al., 2017). These trade-offs were especially relevant in the case of recreational fisheries due to the double contribution of barramundi to the achievement targets for the ecosystem service and biodiversity.

The spatial distribution of the different management zones was arranged to maximise the efficiency of conservation efforts with three different conservation zones and minimise the potential impacts of production zones on the others. Hermoso et al. (2015) demonstrated that by prioritizing the allocation of zones subject to different conservation management regimes the total area in need of strict conservation (freshwater focal zones) could be significantly reduced, enhancing efficiency of conservation efforts. Freshwater focal zones are supported by critical management zones and catchment management zones as proposed by Abell et al. (2007) that maintain ecological processes necessary to ensure the long-term persistence of biodiversity within focal zones. The main role of critical management zones was to ensure the connection between freshwater focal zones and the maintenance of key ecological processes derived from longitudinal connectivity (Ward, & Stanford, 1989). On the other hand, catchment management zones were designed to ensure that land uses in the contributing catchments to freshwater focal zones do not compromise the persistence of the biodiversity and/ or ESS that are aimed to be protected. These additional zones are not exclusively devoted to strict conservation and other uses could be allowed. Here, perennial water, and the associated use of resources by aboriginal communities, was allowed to be represented within these conservation-supporting zones. In order to enhance the effectiveness of conservation efforts the approach demonstrated here also tried to minimise impacts of exploitation of provisioning ESS by allocating production zones spatially disconnected from conservation zones as possible. This resulted agriculture suitability zones mostly allocated in the upper catchment, where some of the higher potential for this ecosystem service occurred, which also maximised distance to the most important areas for biodiversity conservation and maintenance of compatible ESS in the lower catchment. Once more, this disconnection was more difficult to attain for recreation fisheries, given the contribution of barramundi to the achievement of not only ESS targets but also biodiversity conservation. Recreational fisheries zones were, however, located in tributaries avoiding the mainstem, important for connectivity purposes among freshwater focal zones. Accounting for the distribution of demand for ESS could also help refine allocation of production zones, so the areas prescribed for exploitation of provisioning services are close to the areas where the services are demanded (Verhagen, Kukkala, Moilanen, van Teeffelen, & Verburg, 2016).

Previous studies have shown the potential of Marxan with Zones for multizone planning in other realms. It has been used, for example, to minimise economic losses for different fisheries while ensuring adequate conservation for marine biodiversity in California (Klein, Steinback, Watts, Scholz, & Possingham, 2009) or plan for multifunctional landscapes in terrestrial ecosystems in South Africa (Reyers, O'Farrell, Nel, & Wilson, 2012) and Norway (Schröter et al., 2014). However, this is the first time that this multizoning approach has been applied to freshwater ecosystems to plan catchment zoning that explicitly tried to minimise trade-offs and enhance co-benefits between ESS and biodiversity. The approach demonstrated here could be used to address the increasingly complex catchment management context due to the generalised rise in demand for provisioning services (e.g., energy production and water extraction) and diminishing availability of water resources in many areas due to climate change (Vörösmarty et al., 2010). This makes adequate planning that simultaneously accounts for both ESS and biodiversity key to achieving sustainable and efficient provision of multiple interacting services and biodiversity conservation. The number of management zones and their spatial arrangement can be modified to fit the interests and special needs in other catchments and should only be taken as a demonstration example. It is, however, important to define well the role that each management zone plays, as we did by distributing representation targets for biodiversity and ESS across zones, and the interaction between the different features (biodiversity and ESS) being addressed to adequately tackle potential co-benefits and trade-offs. For example, the maintenance of a cultural service, such as permanent water, was considered compatible with biodiversity conservation given the low impact that traditional usage of these areas by aboriginal communities have on biodiversity values. However, these relationships need to be evaluated in each case as cultural services, for example, in other regions might not be as compatible with biodiversity conservation (e.g., Cundill, Bezerra, De Vos, & Ntingana, 2017). Similarly, some provisioning services might be compatible with biodiversity conservation (e.g., Nel et al., 2017) and then help create new conservation opportunities. The approach demonstrated here is not constrained to a certain number of ESS and additional services could be integrated in future applications should information on their spatial distribution be available. This information is increasingly being available given the current efforts on mapping (e.g., Maes et al., 2015) and tools available for modelling ESS, such as ARIES (Villa et al., 2014) or INVEST (Sharp et al., 2016).

The estimates of ESS are based on the potential provided by the Daly River catchment but not necessarily released. Further efforts should be devoted in the future to the assessment not only alternative surrogates for ESS but also incorporate estimates of demand for the different services and the flow between the areas where the ESS exist and where they area demanded. This will help address more realistically the allocation of the different management zones. In this case, for example, most of the agriculture suitability zones were concentrated in the upper part of the catchment, given that this had the highest potential and was far from conservation management zones. The demand for these ESS might display particular spatial patterns that should inform the allocation of the different management zones. This would, however, make the achievement of all representation targets more complex and potentially not feasible.

The contribution of this study is especially relevant given the limited attention that the integration of ESS and landscape planning in freshwater systems has received (Boulton et al., 2016; Martínez-Harms et al., 2015), the increasing threats to these systems worldwide that compromise the future persistence and access to ESS provided by freshwater ecosystems (Vörösmarty et al., 2010), and the importance of freshwater ESS for human wellbeing (e.g., freshwater provision; Millennium Ecosystem Assessment, 2005). This multi-zoning approach could be very valuable towards developing catchment management plans where both human and biodiversity needs are considered and complement the work being developed in other parts of the world, like South Africa (Nel et al., 2011), Spain (Terrado et al., 2016) or South America (Abell et al., 2017), where systematic planning approaches have not been used. Holistic plans should help different stakeholders appreciate their interdependencies at the catchment level (e.g., end users of water depend on maintenance of clean water resources in upstream areas) and inform the implementation of payment for ESS. This should help cover opportunity costs in areas important for the maintenance of the ESS and also fund biodiversity conservation, on which most of these ESS depend.

Acknowledgements

Funding support provided to VH by the Ramon y Cajal Program funded by the Spanish Government (RYC-2013-13979), the Australian Research Council (Discovery Grant DP120103353 to SL and MK; DECRA DE130100565 to SL), the Australian Government Department of Environment through the National Environmental Science Program Northern Australia Environmental Resources Hub, and the Australian Rivers Institute, Griffith University are acknowledged.

References

Abell, R., Allan, J.D. & Lehner, B. (2007) Unlocking the potential of protected areas for freshwaters. *Biological Conservation*, 134, 48–63.

Abell, R., Asquith, N., Boccaletti, G., Bremer, L., Chapin, E., Erickson-Quiroz, A., …, Wood, S. (2017). Beyond the source: the environmental, economic, and community benefits of source water protection. Arlington, VA: The Nature Conservancy.

Acreman, M.C., Harding, R.J., Lloyd, C., McNamara, N.P., Mountford, J.O., Mould, D.J., …, Dury, S.J. (2011). Trade-off in ecosystem services of the Somerset Levels and Moors wetlands. *Hydrological Sciences Journal*, 56, 1543–1565.

Adams, V.M., Alvarez-Romero, J.G., Carwardine, J., Cattarino, L., Hermoso, V., Kennard, M.J., …, Stoeckl, N. (2014). Planning across freshwater and terrestrial realms: cobenefits and tradeoffs between conservation actions. *Conservation Letters*, 7, 425–440.

Adams, V.M. & Pressey, R.L. (2014). Uncertainties around the implementation of a clearing-control policy in a unique catchment in Northern Australia: exploring equity issues and balancing competing objectives. *PLoS One*, 9, e96479.

Adams, V.M., Alvarez-Romero, J.G. & Pressey, B. (2016). Using optimal land-use scenarios to assess trade-offs between conservation, development, and social values. *PLoS One*, 11, e0158350.

Australian Government Department of the Environment. (2012). Australia - Present Major Vegetation Groups - NVIS Version 4.1. Available at: http://www.environment.gov.au/land/native-vegetation/national-vegetation-information-system/data-products.

Atkinson, S.C., Jupiter S.D., Adams V.M., Ingram J.C., Narayan S., Klein C.J. & Possingham H.P. (2016) Prioritising mangrove ecosystem services results in spatially variable management priorities. *Plos One*, 11, e0151992.

Ball, I.R., Possingham, H.P. & Watts, M. (2009) MARXAN and relatives: software for spatial conservation prioritisation. Spatial conservation prioritisation: quantitative methods and computational tools (Eds A. Moilanen, K.A. Wilson & H.P. Possingham), pp. 185–195. Oxford University Press, Oxford.

Balvanera, P., Daily, G.C., Ehrlich, P.R., Ricketts, T., Bailey, S.A., Kark, S., …, Pereira, H. (2001). Conserving biodiversity and ecosystem services. *Science,* 291, 2047.

Ban, C.N. & Klein, C.J. (2009). Spatial socioeconomic data as a cost in systematic marineconservation planning. *Conservation Letters,* 2, 206-2015.

Bryan, B.A., Runting, R.K., Capon, T., Perring, M.P., Cunningham, S.C., Kragt, M.E., …, Wilson, K.A. (2015). Designer policy for carbon and biodiversity co-benefits under global change. *Nature Climate Change*, 6, 301–305.

Carpenter, S.R., Mooney, H.A., Agard, J., Capistrano, D., DeFries, R.S., Díaz, S., … Whyte, A. (2009). Science for managing ecosystem services: beyond the Millennium Ecosystem Assessment. *Proceedings of the National Academy of Sciences USA,* 106, 1305–1312.

Chan, K.M.A., Shaw, M.R., Cameron, D.R., Underwood, E.C. & Daily, G.C. (2006). Conservation planning for ecosystem services. *PLoS Biology,* 4: e379.

Chan, T., Hart, B., Kennard, M.J., Pusey, B.J., Shenton, W., Douglas, M., …, Patel, S. (2012). Bayesian network models for environmental flow decision making in the Daly River, Northern Territory, Australia. *River Research and Applications,* 28, 283-301.

Close, P.G., Dobbs, R.J., Ryan, T.J., Ryan, K., Speldewinde, P.C. & Toussaint, S. (2014). Prediction of potentially significant fish harvest using metrics of accessibility in northern Western Australia. *Journal of the Royal Society of Western Australia*, 97, 355–361.

Cundill, G., Bezerra, J.C., De Vos, A. & Ntingana, N. (2017). Beyond benefit sharing: Place attachment and the importance of access to protected areas for surrounding communities. Ecosystem Services, in press. doi.org/10.1016/j.ecoser.2017.03.011

Dudgeon, D. (2014). Accept no substitute: biodiversity matters. Aquatic Conservation: Marine and Freshwater Ecosystems, 24, 435–440.

Egoh, B., Rouget, M., Reyers, B., Knight, A.T., Cowling, R.M., van Jaarsveld, A.S., Welz, A. (2007). Integrating ecosystem services into conservation assessments: A review. *Ecological Economics,* 63, 714–721.

Egoh, B.N., Reyers, B., Carwardine, J., Bode, M., O'Farrell, P.J., Wilson, K.A., …, Cowling, R.M. (2010). Safeguarding biodiversity and ecosystem services in the Little Karoo, South Africa. *Conservation Biology,* 24, 1021–1030.

ESRI (2011). ArcGIS Desktop: Release 10. Redlands, CA: Environmental Systems Research Institute.

Geoscience Australia. (2006). Geodata topo 250K. Series 3. Geoscience Australia, Canberra. Available at: http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_63999. (Last visited 26 October 2017).

Goldstein, J.H., Caldarone, G., Duarte, T.K., Ennaanay, D., Hannahs, N., Mendoza, G., …, Daily, G.C. (2012). Integrating ecosystem-service tradeoffs into land-use decisions. *Proceedings of the National Academy of Sciences USA,* 109, 7565–7570.

Hermoso, V. & Kennard, M.J. (2012). Uncertainty in coarse conservation assessments hinders the efficient achievement of conservation goals. *Biological Conservation,* 147, 52–59.

Hermoso, V., Kennard, M.J. & Linke, S. (2012). Integrating multi-directional connectivity requirements in systematic conservation planning to prioritise fish and waterbird habitat in freshwater systems. *Diversity and Distributions,* 18, 448–458.

Hermoso, V., Ward, D.P. & Kennard, M.J. (2012). Using water residency time to enhance spatiotemporal connectivity for conservation planning in seasonally dynamic freshwater ecosystems. *Journal of Applied Ecology,* 49, 1028–1035.

Hermoso, V., Linke, S., Possingham, H. & Prenda. (2011). Addressing longitudinal connectivity in the systematic conservation planning of fresh waters. *Freshwater Biology,* 56, 57-70.

Hermoso, V., Cattarino, L., Kennard, M.J., Watts, M & Linke, S. (2015). Catchment zoning for freshwater conservation: refining plans to enhance action on the ground. *Journal of Applied Ecology*, 52, 940–949.

Hermoso, V., Ward, D.P. & Kennard, M.J. (2013). Prioritizing refugia for freshwater biodiversity conservation in highly seasonal ecosystems. *Diversity and Distributions*, 19, 1031–1042.

Howe, C., Suich, H., Vira, B. & Mace, G.M. (2014). Creating win-wins from trade-offs? Ecosystem services for human well-being: A meta-analysis of ecosystem service trade-offs and synergies in the real world. *Global Environmental Change*, 28, 263–275.

Hutchinson, M.F., Stein, J.L., Stein, J.A., Anderson, H. & Tickle, P.K. (2008). GEODATA 9 Second DEM and D8. Digital Elevation Model Version 3 and Flow Direction Grid User Guide. Geoscience Australia. Available at: http://www.ga.gov.au/metadata-gateway/metadata/record/gcat_66006 (Last visited 26 October 2017).

Jackson, S., Finn, M. & Featherston, P. 2012. Aquatic resource use by Indigenous Australians in two tropical river catchments: the Fitzroy River and Daly River. *Human Ecology*, 40, 893-908.

Kennard, M.J. (2010). Identifying high conservation value aquatic ecosystems in northern Australia. Interim Report for the Department of Environment, Water, Heritage and the Arts and the National Water Commission. Tropical Rivers and Coastal Knowledge (TRaCK) Commonwealth Environmental Research Facility. Charles Darwin University, Darwin. ISBN: 978-1-921576-23-2. Available at: http://155.187.2.69/water/publications/policy-programs/pubs/nawfa-hcvae-trial-report.pdf (Last visited 26 October 2017).

King, A.J., Townsend, S.A., Douglas, M.M., Kennard, M.J. (2015). Implications of water extraction on the low-flow hydrology and ecology of tropical savannah rivers: an appraisal for northern Australia. *Freshwater Science*, 34, 741–758.

Klein, C.J., Steinback, C., Watts, M., Scholz, A.J. & Possingham, H.P. (2009). Spatial marine zoning for fisheries and conservation. *Frontiers in Ecology and the Environment,* 8, 349–353.

Leathwick, J.R., Rowe, D., Richardson, J., Elith, J. & Hastie T. (2005) Using multivariate adaptive regression splines to predict the distribution of New Zealand's freshwater diadromous fish. *Freshwater Biology,* 50, 2034–2052.

Linke, S., Kennard, M., Hermoso, V., Olden, J.D., Stein, J. & Pusey, B.J. (2012) Merging connectivity rules and large-scale condition assessment improves conservation adequacy in a tropical Australian river. *Journal of Applied Ecology,* 49, 1036-1045.

Luck, G.W., Chan, K.M.A. & Fay, J.P. (2009). Protecting ecosystem services and biodiversity in the world's watersheds. *Conservation Letters,* 2, 179–188.

Maes J., Fabrega N., Zulian G., Lopes Barbosa A.L., Vizcaino M., Ivits E., …, Lavalle C. (2015). Mapping and Assessment of Ecosystems and their Services: Trends in ecosystems and ecosystem services in the European Union between 2000 and 2010. JRC Science and policy report. Publications Office of European Union, Luxembourg.

Maes, J., Teller, A., Erhard, M., Murphy, P., Paracchini, M., Barredo, J., ..., Petersen, J. (2014). Mapping and assessment of ecosystems and their services—indicators for ecosystem assessments under Action 5 of the EU Biodiversity Strategy to 2020. European Commission, ISBN, pp. 978–992.

Martinez-Harms, M.J., Bryan, B.A., Balvanera, P., Law, E.A., Rhodes, J.R., Possingham, H.P. & Wilson, K.A. (2015). Making decisions for managing ecosystem services. *Biological Conservation,* 184, 229–238.

Millennium Ecosystem Assessment (MEA). (2005). Ecosystems and Human Well-Being: Synthesis. Island Press, Washington, DC.

Mitchell, M.G.E., Suarez-Castro, A.F., Martinez-Harms, M., Maron, M., McAlpine, C., Gaston, K.J., …, Rhodes, J.R. (2015). Reframing landscape fragmentation's effects on ecosystem services. *Trends in Ecology and Evolution,* 30, 190–198.

Morán-Ordoñez, A., Whitehead, A., Luck, G.W., Cook, G., Maggini, R., Fitzsimons, J.A. & Wintle, B.A. (2017). Analysis of trade-offs between biodiversity, carbon farming and agricultural development in Northern Australia reveals the benefits of strategic planning. *Conservation Letters*, 10, 94-104.

Naidoo, R., Balmford, A., Costanza, R., Fisher, B., Green, R.E., Lehner, B., …, Ricketts, T.H. (2008). Global mapping of ecosystem services and conservation priorities. *Proceedings of the National Academy of Sciences USA.* 105, 9495–9500.

Nel, J.L., Le Maitre, D.C., Roux, D.J., Colvin, C., Smith, J.S., Smith-Adao, L.B., Maherry, A. & Sitas, N. (2017). Strategic water source areas for urban water security: Making the connection between protecting ecosystems and benefiting from their services. Ecosystem Services, in press. doi.org/10.1016/j.ecoser.2017.07.013.

Nel, J.L. Driver, A., Strydom, W.F., Maherry, A., Petersen, C., Hill, L., …, Smith-Adao, L.B. (2011). Atlas of Freshwater Ecosystem Priority Areas in South Africa: maps to support sustainable development of water resources. WRC report TT 500/11. Water Research Commission, Pretoria.

Ormerod, S.J. (2014). Rebalancing the philosophy of river conservation. *Aquatic Conservation: Marine and Freshwater Ecosystems*, 24, 147–152.

Pascoe-Bell, A., Green, C., Lynch, B., Hill, J., Tickell, S.J., Cameron, A & Smith, S. (2014). Potential Land for Long-term Sustainable Food Production. Soil and Water Suitability Assessment, 2nd Edition. Department of Land Resource Management. Palmerston, Northern Territory. Available at: http://www.territorystories.nt.gov.au/jspui/handle/10070/238939 (Last visited 26 October 2017).

Pusey, B.J. & Arthington, A.H. (2003). Importance of the riparian zone to the conservation and management of freshwater fishes: a review with special emphasis on tropical Australia. *Marine and Freshwater Research*, 54, 1-16.

Reyers, B., O'Farrell, P.J., Nel, J.L. & Wilson, K. (2012). Expanding the conservation toolbox: conservation planning of multifunctional landscapes. *Landscape Ecology,* 27, 1121–1134.

Sanon, S., Hein, T., Douven, W. & Winkler, P. (2012). Quantifying ecosystem service trade-offs: The case of an urban floodplain in Vienna, Austria. *Journal of Environmental Management*, 111, 159–172.

Schröter, M., van der Zanden, E.H., van Oudenhoven, A.P.E., Remme, R.P., Serna- Chavez, H.M., de Groot, R.S. & Opdam P. (2014). Ecosystem services as a contested concept: a synthesis of critique and counter-arguments. *Conservation Letters*, 7, 514-523.

Sharp, R., Tallis, H.T., Ricketts, T., Guerry, A.D., Wood, S.A., Chaplin-Kramer, R., …, Douglass, J. (2016). InVEST +VERSION+ User's Guide. The Natural Capital Project, Stanford University, University of Minnesota, The Nature Conservancy, and World Wildlife Fund.

Tallis, H. & Polasky, S. (2009). Mapping and valuing ecosystem services as an approach for conservation and natural-resource management. *Annals of the New York Academy of Science,* 1162, 265–283.

Tallis, H., Kareiva, P., Marvier, M. & Chang, A. (2008). An ecosystem services framework to support both practical conservation and economic development. *Proceedings of the National Academy of Sciences USA*, 105, 9457–9464.

Terrado, M., Momblanch, A., Bardina, M., Boithias, L., Munné, A., Sabater, S., Solera, A., & Acuña, V. (2016). Integrating ecosystem services in river basin management plans. *Journal of Applied Ecology*, 53, 865–875.

Tockner, K. & Stanford, J.A. (2002). Riverine flood plains: present state and future trends. *Environmental Conservation*, 29, 308–330.

van Jaarsveld, A.S., Biggs, R., Scholes, R.J., Bohensky, E., Reyers, B., Lynam, T., …, Fabricius, C. (2005). Measuring conditions and trends in ecosystem services atmultiple scales: the Southern African Millennium Ecosystem Assessment (SAfMA) experience. *Philosophical Transactions of the Royal Society B Biological Sciences*, 360, 425–441.

Venter, O., Hovani, L., Bode, M. & Possingham, H.P. (2013). Acting optimally for biodiversity in a world obsessed with REDD+. *Conservation Letters*, 6, 410–417.

Verhagen, W., Kukkala, A.S., Moilanen, A., van Teeffelen, A.J.A., Verburg, P.H. (2016). Use of demand and spatial flow in prioritizing areas for ecosystem services. *Conservation Biology*, DOI: 10.1111/cobi.12872.

Villa, F., Bagstad, K.J., Voigt, B., Johnson, G.W., Portela, R., Honzak, M., & Batker, D. (2014). A methodology for adaptable and robust ecosystem services assessment. PLoS ONE, 9(3), e91001.

Vörösmarty, J.C., McIntyre, P.B., Gessner, M.O., Dudgeon, D., Prusevich, A., Green, P., …, Liermann, C.R. (2010). Global threats to human water security and river biodiversity. *Nature*, 467, 555–561.

Ward J.V. & Stanford J.A. (1989). The four-dimensional nature of lotic systems. Journal of the North American Benthological Society, 8, 2–8.

Watts, M.E., Steinback, C. & Klein, C.J. (2008) Applying Marxan with Zones to North central coast of California. User Guide (available at http://www.uq.edu.au/marxan/, last accessed 8th Sept 2014).

Watts, M.E, Ball I.R., Stewart R.R., Klein C.J., Wilson K., Steinback C., …, Possingham H.P. (2009) Marxan with Zones: software for optimal conservation based land- and sea-use zoning. *Environmental Modelling and Software*, 24, 1513–1521.

Webster, T., Morison, J., Abel, N., Clark, E., Rippin, L., Herr, A., …, Stone P. (2009). Irrigated agriculture: development opportunities and implications for northern Australia (chapter 10). Northern Australia Land and Water Science Review full report: Coordinated by the

Commonwealth Scientific and Industrial Research Organisation (CSIRO). Available at: http://www.industry.gov.au/ONA/Reports-and-publications/Documents/Chapter_10-Irrigated_agriculture.pdf. (Last visited 26 October 2017).

Woinarski, J., Mackey, B., Nix, H. & Traill, B. (2007). The nature of northern Australia. Natural values, ecological processes and future prospects. ANUE Press, Canberra. Available at: http://press.anu.edu.au?p=34501.

Table 1. Ratio between amount of each ecosystem service (ESS) achieved and the specified target, for different target levels. Average (±SE) across all 139 freshwater species is also shown. Values for compatible ESS (Carbon storage/ flood retention, perennial water) and biodiversity correspond to representation achieved within freshwater focal zone, while for incompatible ESS (recreational fisheries, agriculture suitability) are allocated to trade-off zones. Values >1 indicate ESS that have over-achieved the target, while values <1 indicate the proportion of the target achieved.

ESS/ Biodiversity		Target ESS					
		5%	10%	25%	35%	50%	75%
Carbon storage/ flood retention		5.5	2.8	1.1	1.0	1.0	1.0
Perennial water		13.9	6.9	2.8	2.0	1.5	1.0
Recreational fisheries		1.1	1.0	1.0	1.0	1.0	0.5
Agriculture suitability		1.0	1.0	1.0	1.0	1.1	0.8
Biodiversity	(Average)	12.0	12.2	12.8	13.6	18.5	25.3
	(SE)	1.0	1.1	1.2	1.3	2.1	3.2

666 Figure 1.

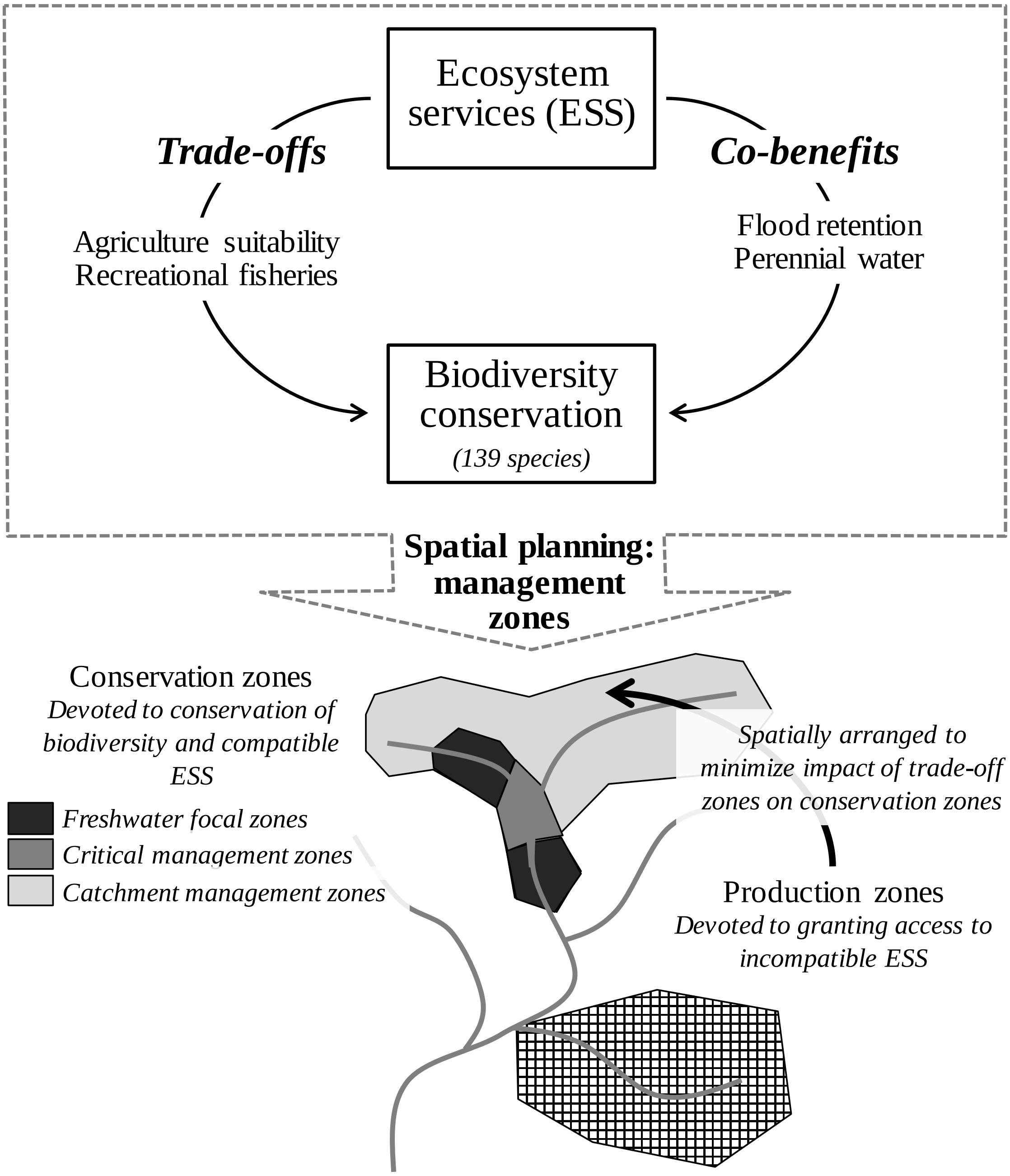
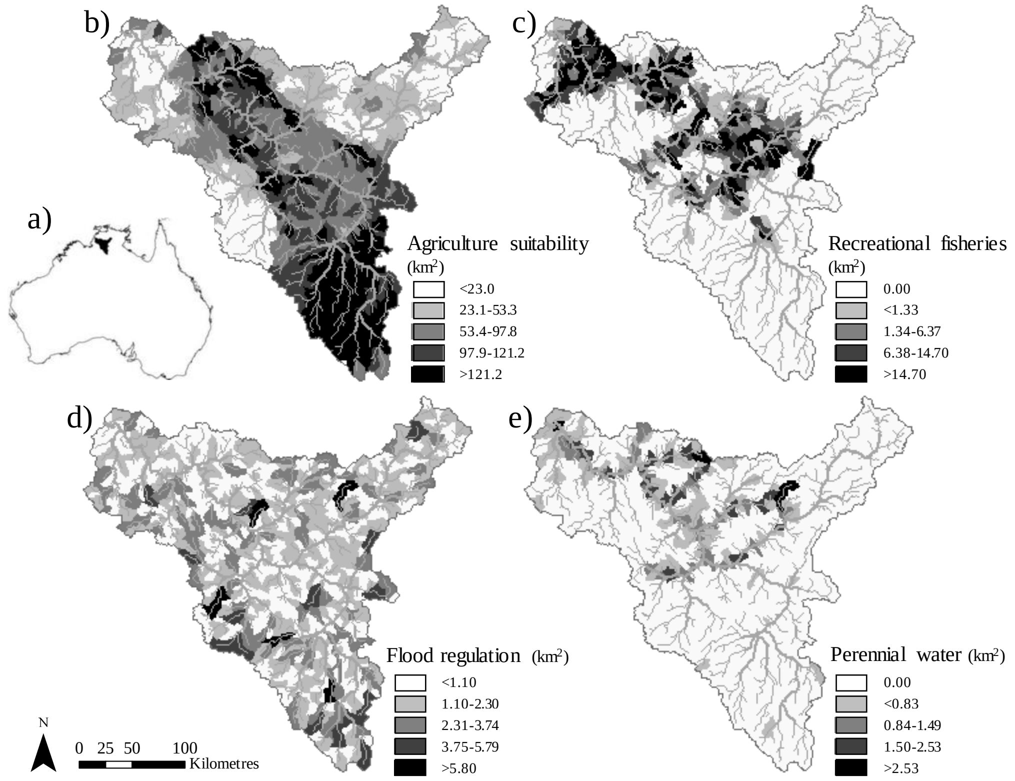
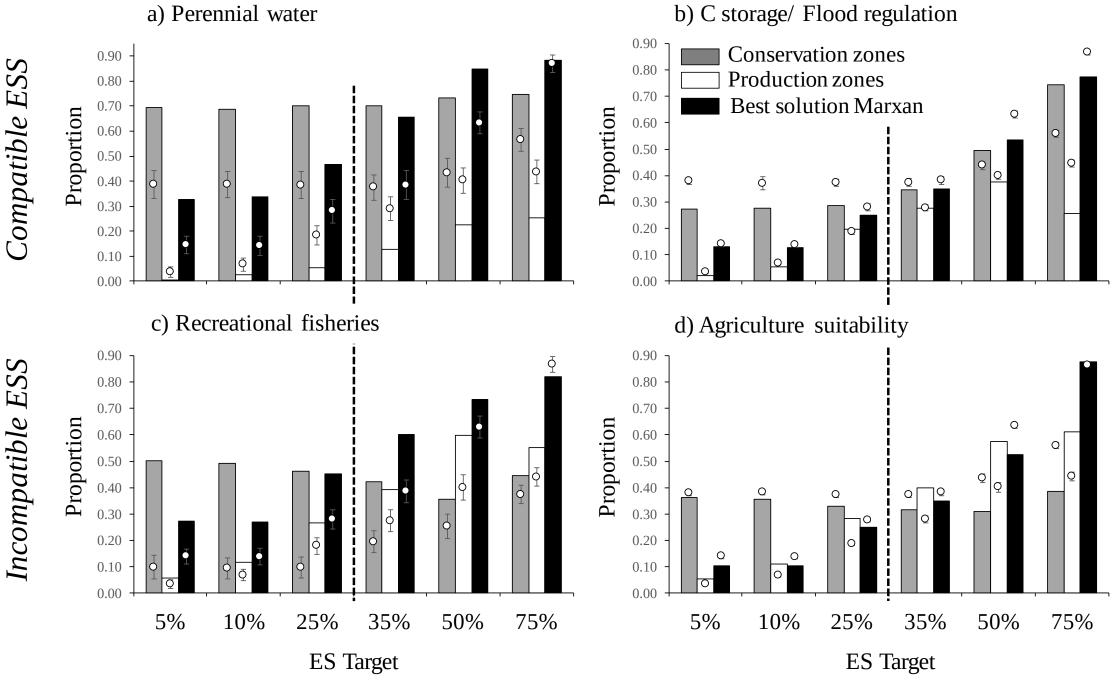

Ecosystem services (ESS)
Trade-offs
Co-benefits
Agriculture suitability
Recreational fisheries
Flood retention
Perennial water
Biodiversity conservation
(139 species)
Spatial planning: management zones
Conservation zones
Devoted to conservation of biodiversity and compatible ESS
Freshwater focal zones
Critical management zones
Catchment management zones
Spatially arranged to minimize impact of trade-off zones on conservation zones
Production zones
Devoted to granting access to incompatible ESS

Figure 2.


a)
b)
c)
d)
e)
Agriculture suitability (km^2)
<23.0
23.1-53.3
53.4-97.8
97.9-121.2
>121.2
Recreational fisheries (km^2)
0.00
<1.33
1.34-6.37
6.38-14.70
>14.70
Flood regulation (km^2)
<1.10
1.10-2.30
2.31-3.74
3.75-5.79
>5.80
Perennial water (km^2)
0.00
<0.83
0.84-1.49
1.50-2.53
>2.53
N
0 25 50 100
Kilometres

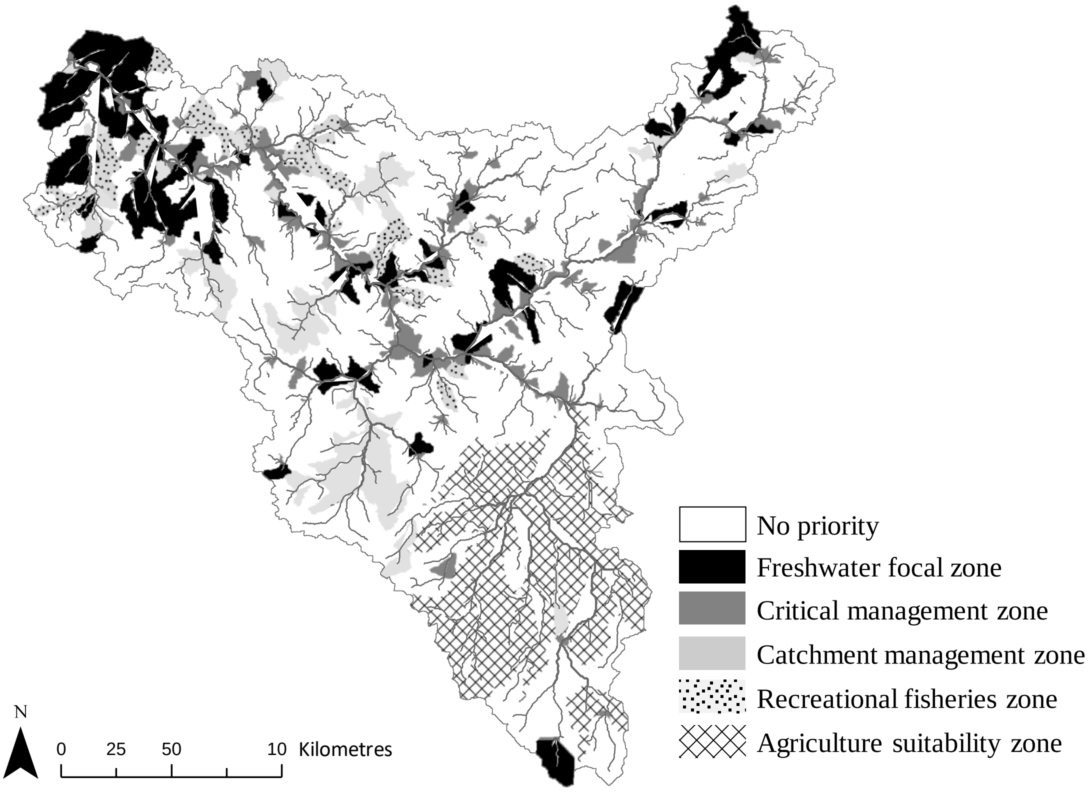
669 Figure 3.



670

671

Figure 4.


No priority
Freshwater focal zone
Critical management zone
Catchment management zone
Recreational fisheries zone
Agriculture suitability zone
N
0
25
50
10
Kilometres