Measuring benefits of protected area management: trends across realms and research gaps for freshwater systems

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Supplementary Materials

Contrasting possible confounders and outcome measurements for freshwater and terrestrial systems.

Our theory of change for protection suggests that threats associated with extractive uses will be addressed by removing the threat through the act of protection (i.e. prevention) while other environmental threats are addressed by management within protected areas (e.g. habitat restoration or remediation, fire management and invasive species control). We therefore select four threats (selected from [40]) to identify the similarities and differences in confounders across different realms (specifically terrestrial and freshwater) ensuring that two are extractive uses (human infrastructure, agriculture and aquaculture) and two are other environmental threats (natural system modifications and invasive species). For each threat we list the expected outcome associated with protection or management, a measurement of the outcome, connectivity issues that might impact the outcome, confounding factors and variables available to include in evaluation design to control for these factors. We address possible confounding factors - extraneous variables that correlated with both the selection and outcome of treatment - and selection bias - where reasons that a unit is selected for treatment also affect the outcome - that should be considered and controlled for (Supplementary Table 1).

An important finding emerges from Supplementary Table 1: many of the confounding factors are similar across the two realms and relate to suitability of the resource for extractive pressures and proximity to market or suitability of the resource as it relates to a threat like invasive species and exposure to the threat such as presence of spread vectors. Therefore, variables used in terrestrial systems to control for confounding factors such as slope, climatic variables, distance to population and distance to roads will likely be of use in freshwater systems and can be a good starting point for stating causal hypotheses and elucidating possible confounders. Measures of outcomes will of course vary across terrestrial and freshwater realms; however freshwater-specific measures such as hydrology and geomorphology (e.g. aquifer size, groundwater connectivity, water availability) may be readily available because they are routinely collected for other purposes such as gauging of river systems and licence applications for water extraction or bores. The main difference between terrestrial and freshwater systems that emerges from the table is the information required for freshwater systems on hydrologic connectivity, and spatial configuration of threats such as water extractions, dams or invasive species distributions. In order to account for this, an understanding of the system is required at a larger spatial extent compared to terrestrial systems in which most connectivity issues relate to neighbouring units (e.g. forest cover or fire regimes in neighbouring forest).

Supplementary Table 1. Examples of four threatening processes [40] and possible sources of selection bias (factors associated with placement of protection and outcomes from protection and management): (1) Infrastructure development (includes development associated with residential, industrial and transportation activities developments), (2) Agriculture and aquaculture, (3) Altered fire regimes (as a specific example of natural system modifications), (4) Invasive species. Possible sources of bias are divided into two types: Natural resource characteristics, and Resource User qualities.

Infrastructure development					
Realm	**Protection outcome**	**Outcome measure**	**Connectivity issues**	**Selection bias**	**Variables**
Terrestrial	maintain or increase forest cover	Forest cover	Edge effects on forest cover loss - control by considering neighbouring forest cover outside PA	1) Areas that are more accessible or more aesthetically pleasing may be more likely to be converted for human development. 2) Edge effects on forest cover mean that forest that is next to cleared areas may be more likely to experience higher natural rates of forest cover loss	1) distance to road, distance to town, population density, slope, aesthetic and amenity qualities such as distance to coast 2) forest cover of neighbouring areas
Freshwater	maintain or return to original hydrology	Seasonal flow of surface water	Extractions outside of protected area - control by considering upstream water groundwater connections/extractions	1) Areas with larger freshwater resources suitable for extraction (e.g. large aquifer) may be more likely to be converted for human development due to their ability to support demand for water for consumptive uses. 2) Connectivity of water resources means that upstream extractions and groundwater extractions may affect seasonal flows over broad spatial extent	1) Water availability and quality, aquifer size, groundwater connectivity, geomorphology 2) upstream extraction and extraction of connected groundwater system
Agriculture and aquaculture					
	Protection outcome	**Outcome measure**	**Connectivity issues**	**Selection bias**	**Variables**
Terrestrial	maintain or increase forest cover	Forest cover	Edge effects on forest cover loss -control by considering neighbouring forest cover outside PA	Land that is more productive may be less likely to be protected and more likely to be converted. Accessibility to markets may also influence likelihood of conversion.	Access to resource for development: distance to road, distance to town, population density

Freshwater	maintain or return to original hydrology	Seasonal flow	Extractions outside of protected area - control by considering upstream water groundwater connections/extractions	More productive water resources (e.g. constant flowing rivers or large aquifers) may be less likely to be protected and more likely to be converted. Accessibility to markets may also influence likelihood of conversion.	Access to resource for development: distance to road, distance to town, population density
Altered fire regimes (Natural system modification)					
	Protection outcome	**Outcome measure**	**Connectivity issues**	**Selection bias**	**Variables**
Terrestrial	maintain or return to natural fire regime	Time since last fire	Fire history of neighbouring units	1) Areas that experience altered fire regimes such as increased fire frequency and intensity are potentially less attractive for development and are thus more likely to be protected and will need intensive management once protected. 2) Areas with neighbouring properties with different fire regimes may experience more or less exposure to possible ignition.	1) Combustibility surrogates such as vegetation type and time since last fire 2) Exposure to ignition such as surrounding land use and distance to road.
Freshwater	maintain or return to natural fire regime	Time since last fire	Fire history of catchment	1) Areas that experience altered fire regimes such as increased fire frequency and intensity are potentially less attractive for development of water resources (e.g. may have increased sedimentation) and are thus more likely to be protected and will need intensive management once protected. 2) Catchment influences on riparian zones and streams mean that upstream fires can effect nutrients in downstream freshwater systems thus connectivity of system, slope and nutrient status of catchment should be controlled for	1) Combustibility surrogates such as vegetation type and time since last fire 2) Slope, vegetation cover, nutrient status of catchment, upstream fire regime

Invasive Species					
	Protection outcome	**Outcome measure**	**Connectivity issues**	**Selection bias**	**Variables**
Terrestrial	reduce invasive species density	Invasive species cover	Distance to nearest source population and presence of spread vectors such as animals or roads	1) Areas that have high densities of invasive plants may not be suitable for intensive development uses such as cropping due to increased production costs and therefore may be less likely to be converted, more likely to be protected, and will need intensive management once protected. 2) Areas with neighbouring invasions may experience higher propagule pressure and thus higher spread rates and re-invasion rates.	1) Suitability for invasive species such as soil, climatic variables. 2) Distance to nearest source population and spread pathways such as road
Freshwater	reduce invasive species density	Invasive species cover	Distance to nearest source population (taking into consideration that nearest population will be related to connectivity of aquatic system and flow direction) and presence of spread vectors such as animals	1) Areas that have high densities of invasive plants may not be suitable for development of water resources, e.g. due to restriction of water flow from dense infestations, and therefore may be less likely to be converted, more likely to be protected, and will need intensive management once protected. 2) Areas with neighbouring invasions or high human visitation rates may experience higher propagule pressure and thus higher spread rates and re-invasion rates. Seeds of aquatic weeds can be transported long distances downstream and thus connectivity of aquatic systems is an important consideration.	1) Suitability for invasive species such as soil, climatic variables. 2) Distance to nearest source population (upstream) and spread pathways such as transport down rivers.