The MPA Guide Expanded Guidance: Outcomes

Version 1 (September, 2021)

Also Table S1 in Supplementary Materials for Grorud-Colvert et al. 2021, "The MPA Guide: A Framework to Achieve Global Goals for the Ocean", *Science*

Expanded Ecological Outcomes of MPAs according to Level of Protection. The outcomes assume that best practices in Enabling Conditions (CONDITIONS) have been met, key threats are abatable by the MPA, and the system has had time to progress from a degraded state to one with relatively few fluctuations. While some ecological benefits occur quickly following protection (e.g., *1*), it can take time for many benefits to accrue. Levels of confidence in the outcome represent expert judgements based on available research (see References). Supporting references for each outcome are not exhaustive but are representative of this evidence.

Outcome	**Level of protection**				**Confidence in effect / Supporting references**
	Fully	**Highly**	**Lightly**	**Minimally**	
Biodiversity conservation					
Many attributes of individual organisms, their populations, and their communities contribute to the overall persistence and resilience of species and ecosystems, and the benefits they provide to people. The cells to the right of each outcome describe the extent to which different levels of protection are likely to protect or restore that attribute.					
Abundance: maintained at or increases towards pre-exploitation levels ● In general, protection results in increases in abundance of organisms within the MPA. ● What increases, by how much, and when depend on the level of protection and degree of previous exploitation or impact. ● Previously exploited species generally increase more	Abundances are maintained in unimpacted sites or they increase towards unexploited / unimpacted levels, including many species highly vulnerable to depletion.	Abundances increase, including some species highly vulnerable to depletion, but for those still targeted to lower levels than with full protection.	Species that are given specific protections may increase in abundance. Vulnerable species may be present at low population levels.	Minimal change or continued decline of overexploited or impacted species.	High confidence Côté et al. 2001 (*1*); Lester and Halpern 2008 (*2*); Claudet et al. 2008 (*3*); Lester et al. 2009 (*4*); Giakoumi et al. 2017 (*5*); Zupan et al. 2018 (*6*)

rapidly than other species. ● The prey of these previously exploited species will likely decrease in abundance as their predators recover, indicating that the ecosystem is recovering.					
Population age structure: maintained at or extends towards natural age structure ● Once protected, previously exploited or impacted species (e.g., bycatch) live longer, particularly predators. ● This shifts the population structure towards larger, older individuals that usually invest more in reproduction, are more experienced (e.g. in finding mates or favorable spawning areas), may produce higher quality offspring and	Older individuals will gradually return to the population, with timelines dependent upon growth rates of the species.	Older individuals will gradually return to the population if they are not exploited.	Species that are given specific protections live longer; exploited or impacted species will not.	Minimal difference in population structure compared to unprotected sites.	High confidence Roberts et al. 2001 (*7*); Claudet et al. 2006 (*8*); Ruttenberg et al. 2011 (*9*); García-Rubies et al. 2013 (*10*); Abesamis et al 2014 (*11*); Malcolm et al. 2015 (*12*); Harasti et al. 2018 (*13*)

can buffer the population through multi-year periods of environmental conditions unfavorable to replenishment.					
Biomass: maintained at or increases towards pre-exploitation levels ● Protection generally results in increases in abundance and larger average body sizes, leading to large increases in biomass of previously exploited or impacted species.	Biomass is maintained at unexploited /unimpacted levels or recovers towards this.	Biomass is maintained at unexploited / unimpacted levels or it increases. For exploited or impacted species, biomass is at lower levels.	Those species that are given specific protections will increase in biomass. Exploited or impacted species will stay at depleted levels or continue to decline.	Minimal difference in biomass compared to unprotected sites.	High confidence Lester and Halpern 2008 (*2*); Lester et al. 2009 (*4*); Sala et al. 2012 (*14*); Guidetti et al. 2014 (*15*); Giakoumi et al. 2017 (*5*); Giakoumi 2018 (*16*); Zupan et al. 2018 (*6*); Agnetta et al. 2019 (*17*)
Species richness (no. of species): increases as populations recover ● Protection results in an increase in the number of species as populations recover, rare species become more common, and vulnerable, previously absent, species recolonize.	Richness is maintained in previously unexploited areas or it recovers towards unimpacted levels.	Richness is maintained (in previously unexploited areas) or it recovers to higher levels.	There is little difference in overall richness, although species with specific protections have an increased frequency of occurrence.	Minimal difference in richness compared to unprotected sites.	High confidence Lester and Halpern 2008 (*2*); Russ and Alcala 2011 (*18*); Nash and Graham 2016 (*19*)
Reproductive output and replenishment: increases as populations recover	Reproductive output of most previously	Reproductive output increases are	Some increases in reproductive output are	Minimal difference in reproductio	High confidence

• Because bigger animals generally produce vastly greater numbers of young than do smaller animals, and because animals live longer when not exploited, far more young are produced in protected areas. • Bigger animals may also be more successful at reproducing and producing higher quality offspring that survive better.	depleted populations can increase several times and in some cases by tens to more than a hundred times.	substantial for most previously depleted populations.	seen for those species given specific protections.	n compared to unprotected sites.	Nemeth 2005 (*20*); Kaiser et al. 2007 (*21*); Crec'hriou et al. 2010 (*22*); Taylor and McIlwain, 2010 (*23*); Díaz et al. 2011 (*24*); Hixon et al. 2014 (*25*); Barneche et al. 2018 (*26*); Marshall et al. 2019 (*27*)
Connectivity of populations: higher self-replenishment and export of offspring as populations recover • In protected areas, the larger production of eggs or other propagules can lead to faster replenishment of the population within the MPA, but also higher export of offspring and therefore greater replenishment	Egg/larvae/ propagule export is enhanced for most species.	Egg/larvae/ propagule export is enhanced for many species.	Egg/larvae/ propagule export is enhanced only for a few species.	Minimal difference in egg/larvae/ propagule export compared to unprotected sites.	Moderate confidence Pelc et al. 2010 (*28*); Christie et al. 2010 (*29*); Di Franco et al. 2012 (*30*); Roberts and Hawkins 2012 (*31*); Andrello et al. 2017 (*32*); Roberts et al. 2017 (*33*); Manel et al. 2019 (*34*); Assis et al. 2021 (*35*)

outside the MPA, sometimes over long distances.					
Rare and endangered species protected: increased protection allows populations to recover ● Some species are more vulnerable to exploitation and damage than others, sometimes even at low intensities of human use.	MPAs provide refuge for and enhance populations of many rare and endangered species, especially sessile, sedentary, or low mobility species.	MPAs provide refuge for and enhance populations of some rare and endangered species, especially sessile, sedentary, or low mobility species, but at lower levels than with full protection for these species.	Rare and endangered species given specific protections are present, especially if they are sessile, sedentary, or low mobility species, but at lower levels than with full or high protection	Minimal differences compared to unprotected sites.	Moderate confidence Mouillot et al. 2008 (*36*); Pichegru et al. 2010 (*37*); Gormley et al. 2012 (*38*); Goetze et al. 2015 (*39*); McLaren et al. 2015 (*40*); Dwyer et al. 2020 (*41*)
Genetic diversity: enhanced as populations recover and habitat heterogeneity increases ● Large population sizes and increased environmental heterogeneity promote genetic diversity, although the effect may be limited for species that have been through population bottlenecks.	Genetic diversity is maintained or enhanced for most species.	Genetic diversity is maintained or enhanced for many species.	Genetic diversity is maintained or enhanced for some species.	Minimal difference in genetic diversity compared to unprotected sites.	Moderate confidence Miethe et al. 2009 (*42*); Fidler et al. 2018 (*43*); Jones et al. 2018 (*44*); Sørdalen et al. 2018 (*45*)

(Environmental heterogeneity refers to the diversity of habitats which will increase as sensitive and vulnerable habitats recover.) ● Genetic diversity may also be enhanced by the different selective environment MPAs provide compared to unprotected areas.					
Habitats: recover over years to decades ● Habitats will recover over timescales of years to decades as habitat-forming species (seaweeds, seagrass, coral, oysters, etc.) benefit from protection and produce cascading ecological effects of protection throughout the ecosystems.	Full recovery of all habitats is possible, but timescales depend on the types of habitats present or able to re-establish. Greater three dimensiona l complexity develops.	Many habitats recover fully or partially, but timescales depend on the types of habitats present. Greater three dimensiona l complexity develops.	Some habitats recover partially.	Minimal difference from unprotected sites in habitat condition or types of habitats present.	High confidence Guidetti 2007 (*46*); Babcock et al. 2010 (*47*); Costello 2014 (*48*); Williamson et al. 2014 (*49*); Turnbull et al. 2018 (*50*)
Ecosystem functioning: natural interactions and processes recover	Full recovery of natural levels of	Partial recovery toward re-established	Food web effects of protection are quite	Minimal difference compared to	Moderate confidence

• As targeted species recover, they will re-establish interactions with other species in the community. • This in turn alters other interactions that may reverberate throughout the community. • Ecosystem-level changes will often be most dramatic when the targeted species were high-level/apex predators, habitat-forming or keystone species.	trophic structure and complexity for most species and habitats; partial recovery for those where key species are highly mobile or migratory.	levels of trophic structures and complexity.	limited and incomplete.	unprotected sites.	Guidetti 2006 (*51*); Claudet et al. 2010 (*52*); Babcock et al. 2010 (*47*); McClanahan and Graham 2015 (*53*); Russ et al. 2015 (*54*); Acuña-Marrero et al. 2017 (*55*); Selden et al. 2017 (*56*)
Ecosystem resilience (ability to recover after disturbance): maintained at or increases towards pre-exploitation levels • Restoration of natural ecological interactions, higher population sizes, and associated increased genetic diversity will likely enhance the resilience	Resilience increases significantly.	Resilience increases.	Little apparent increase in resilience.	Minimal or no apparent increase in resilience.	Low confidence McLeod et al. 2008 (*57*); Ling et al. 2009 (*58*); Micheli et al. 2012 (*59*); Barnett and Baskett, 2015 (*60*); Mellin et al 2016 (*61*); Wilson et al. 2020 (*62*)

of the community within the MPA.					
Effects on exploited species					
The level of protection of each MPA or zone can have important impacts on exploited species. The cells to the right of each outcome describe the extent to which different levels of protection are likely to protect or recover these populations, and the benefits they provide to people.					
Spillover: net movement of targeted mobile animals and some seaweeds to adjacent fishing grounds ● Spillover typically to a maximum of a few kilometers away, as population densities rise and conditions become more crowded. Spillover is often first noticed as an increase in fishery catch rates just outside the MPA (or their no-take zone) boundaries. ● Level of spillover varies by species, and is highly dependent on species' mobility, habitat conditions and level of fishing	Spillover increases significantly with time as populations recover strongly inside MPAs. Bigger fish inside MPAs produce proportionally more larvae leading to potential spillover.	Spillover increases with time as populations recover inside MPAs. Rates of spillover and numbers of species showing the effect are lower than under full protection.	Spillover may increase for species given specific protections.	Minimal spillover to adjacent areas.	High confidence Abesamis and Russ 2005 (*63*); Halpern et al. 2009 (*64*); Russ and Alcala 2011 (*18*); Roberts and Hawkins 2012 (*31*); Di Lorenzo et al. 2016 (*65*); Di Lorenzo et al. 2020 (*66*)

outside of the protected area					
Larval export: maintained at or increases towards pre-exploitation levels ● Increased abundance and body size, plus reduced disturbance enhances reproductive output, usually results in the export of eggs and larvae from the MPA to surrounding areas.	Very high rates of egg and larval export are observed, and they increase with time. Bigger fish inside MPAs produce proportionally more larvae enhancing potential larval export.	High rates of egg and larval export are observed, and they increase with time, but at lower levels than with full protection.	Egg and larval export are higher for those species given specific protections, and they increase with time.	Minimal change in egg and larval export following protection.	High confidence Manríquez and Castilla, 2001 (*67*); Planes et al. 2009 (*68*); Christie et al. 2010 (*29*); Crec'hriou et al. 2010 (*22*); Pelc et al. 2010 (*28*); Harrison et al. 2012 (*69*); Di Franco et al. 2015 (*70*)
Insurance against management failure or stock collapse: protects a portion of the population from exploitation ● Increased abundance and body size, extended population age structures and increased reproduction reduce the likelihood that overfishing outside the MPA causes stock collapse, and they promote recovery following management problems in	Insurance value potentially very high and rises with time since protection and with area protected.	Insurance value potentially high and rises with time since protection and with area protected.	Some insurance value for species given specific protections, but the effect is likely to be low.	Minimal or no apparent insurance value.	Moderate confidence Lauck et al. 1998 (*71*); Roberts et al. 2005 (*72*); Russ and Alcala 2011 (*18*); Krueck et al. 2017 (*73*)

fishing grounds.					
Protection of vulnerable life stages: enhanced via nursery grounds, spawning aggregations, etc., including for highly migratory species ● Protection promotes survival and growth and reduces impacts of overfishing.	Benefits could be very high if key areas of vulnerability (e.g. spawning aggregations) are fully protected in MPAs.	Benefits could be high if key areas of vulnerability are highly protected in MPAs.	Some benefits evident for key areas of vulnerability given specific protection.	Minimal benefits.	High confidence Beets and Friedlander 1999 (*74*); Planes et al. 2000 (*68*); Rogers-Bennett and Pearse 2001 (*75*); Sala et al. 2001 (*76*); Mumby et al. 2004 (*78*); Garla et al. 2006 (*77*); Nemeth 2005 (*20*); Armsworth et al. 2010 (*78*); Grüss et al. 2014 (*79*); Erisman et al. 2017 (*80*); Farmer et al. 2017 (*81*); Sadovy de Mitcheson et al. 2020 (*82*)
Water quality					
The level of protection of each MPA or zone can have important impacts on water quality. The cells to the right of each outcome describe the extent to which different levels of protection are likely to protect or restore water quality, and the benefits this provides to people.					
Eutrophication: reduced, lower likelihood of dead zones, harmful algal blooms, etc. ● More intact pelagic and benthic food webs can increase grazing	Possible	Possible	Unlikely	Unlikely	Low confidence Olds et al. 2014 (*83*); Alongi et al. 2015 (*84*); McKinnon et al. 2017 (*85*); Bergstrøm et al. 2019 (*86*);

rates/nutrient cycling/detritivory, reducing adverse effects of nutrient enrichment. ● More intact pelagic food webs can reduce the probability of harmful algae species from blooming, although even for highly and fully protected MPAs, the effect likely to be offset if there is excessive nutrient pollution.					Strain et al. 2019 (*87*)
Pathogens and pollutants: reduced concentrations ● High densities of filter feeders may reduce nutrient and pathogen levels in overlying water and vegetated habitats have biocidal properties. ● Disease mitigation for species such as corals through reductions in physical injury in areas where human activities are	Reduced pathogen levels likely compared to unprotected sites. Effects may also extend to adjacent areas. Evidence of reduced levels of coral disease in fully protected areas due to lower levels of coral	Reduced pathogen levels likely compared to unprotected sites. Effects may also extend to adjacent areas. Minimizing impacts from other pressures (e.g. fishing) has been shown to increase resilience to coral disease.	Reduced pathogen levels possible, especially where vegetated habitats are included. Impacts from fishing (e.g. abandoned fishing line) can exacerbate instances of coral disease. If protected from mobile	Minimal difference from unprotected sites.	Moderate confidence Cotou et al. 2005 (*88*); Durrieu de Madron et al. 2005 (*89*); Lamb et al. 2017 (*90*); Pollack et al. (2014) (*91*)

reduced. May improve ecosystem resilience by preserving ecosystem function. ● Mobile fishing gears can resuspend sediments and legacy pollutants (e.g. DDT, PCBs, heavy metals) at a higher rate than natural disturbances, reintroducing them to demersal and pelagic food webs. Protection from mobile gears increases longevity and efficacy of storage.	damage and lower abundance of abandoned fishing line. Higher rates of uptake and sequestration of legacy chemicals by seabed invertebrates with longer sediment residence time.	Higher rates of uptake and sequestration of legacy chemicals by seabed invertebrates with longer sediment residence time.	fishing gears, higher rates of uptake and sequestration of legacy chemicals by seabed invertebrates with longer sediment residence time.		
Suspended sediment: reduced levels • Re-establishment of dense populations of filter-feeding invertebrates will increase water filtration rates and reduce suspended sediment. In addition, improved water clarity can foster an increase in	Dense populations of filter-feeders re-establish on the seabed, increasing water clarity, and the abundance of rooted aquatic vegetation especially in semi-enclosed water bodies.	Dense populations of filter-feeders re-establish on the seabed, increasing water clarity and abundance of rooted aquatic vegetation, especially in semi-enclosed water bodies.	If protected from mobile fishing gears, dense populations of filter-feeders may re-establish on the seabed, increasing water clarity, and allowing for the persistence of rooted	Minimal difference from unprotected sites.	Low confidence State of Queensland, 2018 (*92*); Powell et al. 2019 (*93*)

rooted aquatic vegetation (such as seagrasses) which provides important fish nursery habitat.			aquatic vegetation especially in semi-enclosed water bodies.		
Climate resilience/adaptation/mitigation					
The level of protection of each MPA or zone can play an important role in climate resilience, adaptation, and mitigation. There is high confidence in the first-principle knowledge about how marine systems sequester and store carbon; however, more studies are needed about how MPAs specifically contribute to the carbon budget. The cells to the right of each outcome describe the extent to which different levels of protection are likely to impact the changing climate, and the benefits this provides to people.					
Carbon: sequestration and storage enhanced and safeguarded ● Greater primary production by vegetated habitats such as mangroves, salt marshes, and seagrasses protected in MPAs leads to greater carbon capture (e.g., blue carbon). ● Existing stores of carbon in sediments in MPAs are protected from disturbance from mobile fishing gears and other sources. ● Untrawled and undredged seabed habitats promote carbon uptake by richer communities of filter feeding	High, if MPA protects blue carbon coastal habitats such as mangroves, salt marshes and seagrasses, other marine communities that sequester carbon, and/or protects sediments from mobile fishing gears or other sources of disturbance	High, if MPA protects blue carbon coastal habitats such as mangroves, salt marshes and seagrasses, other marine communities that sequester carbon, and/or protects sediments from mobile fishing gears or other sources of disturbance	Moderate, but only if MPA provides some protection to vegetated coastal habitats, and/or to sediments from mobile fishing gears and other sources of disturbance	Minimal difference compared to unprotected sites.	Moderate confidence High confidence in first principle-based knowledge of carbon sequestration and storage in marine systems. Pendleton et al. 2012 (*94*); Atwood et al. 2015 (*95*); Mineur et al. 2015 (*96*); Zarate-Barrera and Maldonado 2015 (*97*); Krause-Jensen and Duarte 2016 (*98*); Howard et al. 2017 (*99*); Roberts et al. 2017 (*33*);

organisms and plants, and storage in sediments. ● Pelagic habitats with high abundance of mesopelagic species promote carbon shuttling from surface to deep water. ● High abundances of animals that feed deep and excrete nutrients at the surface enhance surface productivity, some of which is eventually stored in deep sea sediments.					Duarte et al. 2020 (*100*); Mariani et al. 2020 (*101*); Saba et al. 2021 (*102*); Sala et al. 2021 (*103*)
Acidification: local effects mitigated ● Vegetated areas may reduce local acidification. This may benefit local shellfish or other economically or culturally important species. ● Carbonate excretion at surface by vertically migrating fish	Vegetated habitats increase in extent and quality, especially if supplement ed by active restoration/ coastal realignment , mitigating local acidificatio n. Protection of vertically migrating	Vegetated habitats increase in extent and quality, especially if supplement ed by active restoration/ coastal realignment , mitigating local acidificatio n. Protection of vertically migrating	Given specific protection, vegetated habitats may increase in extent and quality, especially if supplement ed by active restoration, mitigating local acidificatio n. Protection of	Minimal difference from unprotected sites. However, MPAs supporting seaweed aquaculture may have benefits in amelioratin g local acidificatio n.	Low confidence Unsworth et al. 2012 (*104*); Roberts et al. 2017 (*33*); Duarte et al. 2017 (*105*); But see Koweek et al., 2018 (*106*)

may buffer surface acidity. ● Seaweed aquaculture may reduce acidification.	species facilitates surface buffering.	species can facilitate surface buffering.	vertically migrating species can facilitate surface buffering.		
Productivity: declines from climate change offset ● Greater potential for adaptation and sustained productivity due to higher genetic diversity. ● Climate change is reducing marine productivity. With MPAs, primary productivity may be maintained by a greater abundance of marine life playing key roles in the nutrient pump (shuttling of nutrients from depth to epipelagic zone), which promotes primary production. ● Expanded area of coastal vegetated habitats increases productivity	Maintained or increased productivity.	Maintained or increased productivity.	Maintained or increased productivity if specific protections target key ecosystem components promoting productivity.	Minimal difference from unprotected sites.	Low confidence Grémillet and Boulinier 2009 (*107*); Reed et al. 2016 (*108*); Kelly et al. 2017 (*109*); But see Rogers-Bennett and Catton 2019 (*110*)

and nutrient subsidy to adjacent ecosystems. ● Secondary productivity declines can be countered by increased populations of previously exploited species.					
Coastal protection: disturbances offset, maintained, or enhanced ● Protection of biogenic habitats, such as mangroves, seagrasses, saltmarsh, coral reef and oyster beds, can protect coasts even as sea levels rise. This has benefits to human health, safety and security, and economies.	Natural coastal defenses are maintained or enhanced, especially if supplemented by active restoration/ coastal realignment.	Natural coastal defenses are maintained or enhanced, especially if supplemented by active restoration/ coastal realignment.	Natural coastal defenses are maintained or enhanced if given specific protection, especially if supplemented by active restoration/ coastal realignment.	Minimal difference from unprotected sites.	High confidence. Luo et al. 2015 (*111*); Miteva et al. 2015 (*112*); Narayan et al. 2016 (*113*); Roberts et al. 2017 (*33*); Harris et al. 2018 (*114*); Powell et al. 2019 (*93*); Duarte et al. 2020 (*100*)

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