Appendix A: Definitions of Key Concepts

   Catastrophic Regime Shifts

The possibility of a catastrophic regime shift from a cryptic urchin-kelp forest equilibrium to a kelp depauperate-urchin barren equilibrium is an example of an ecological tipping point phenomenon, arising in systems that exhibit multiple steady state equilibria, such that abrupt shifts/tips between the equilibrium states are possible. Gradual changes in an environmental parameter, or one like predator or grazer density, make it more likely that a pulse perturbation will lead to abrupt shifts in a variable like urchin or kelp density (Holling, 1973; Carpenter et al., 2001; Levin and Lubchenco, 2008). The predator-urchin-kelp system is usually characterized as a trophic cascade (Estes and Palmisano, 1974) with two trophic interactions, predator (e.g., spiny lobster (order *Decapoda*) or sea otters (*Enhydra lutris*))-urchin and urchin-kelp. As a result, there are joint equilibria with possibilities for two cascading shifts, a shift from a low-density community of cryptic urchins to a high-density urchin barren and a shift from a high-density kelp forest to a kelp depauperate community. For each, there is potentially a reverse shift, although it may be more difficult to achieve.

   Resilience

Although it may not be the driver, resilience, or lack thereof, is always implicated in catastrophic regime shifts. Resilience describes dynamic behavior in response to pulse perturbations from an equilibrium. Pulse perturbations are short single or periodic disturbances. They may be of stochastic magnitude and are caused by exogenous abiotic factors or population dynamics at other locations in the metacommunity (Yang et al., 2008; Guzman et al., 2019). At a given urchin density, a kelp forest equilibrium's resilience is the tendency for a pulse perturbation in kelp density from that equilibrium to be attracted back to it, rather than being induced toward a kelp depauperate equilibrium. It can be translated into a resilience probability that depends on the size of the equilibrium's basin of attraction and on the probability distribution for the size of the perturbation or, equivalently, the distribution of perturbation displacement locations. Resilience for a kelp depauperate equilibria can be similarly characterized, as it can for a cryptic urchin or urchin barren equilibria (Carpenter et al., 2001) . The resilience probability of an equilibrium can be equal to one (perfect resilience-all perturbations return to it), less than one but greater than zero (partial resilience-displacement locations close to the equilibrium return to it) or zero (the equilibrium disappears). When the resilience of the originating equilibrium is partial, a shift to the alternative equilibrium can be instigated by a perturbation displacement location outside the original equilibrium's basin of attraction. Otherwise, it will occur only if the original equilibrium has zero resilience (Beisner et al., 2003; van Nes et al., 2016).

   Hysteresis

Hysteresis, or hysteretic memory, means that the probability of a perturbation landing in a particular basin of attraction depends on which equilibrium it was perturbed from. Figure S1 shows two equilibria, a low kelp equilibrium at $K_l = 0$ and a high kelp equilibrium at $K_h = 10$.

Each has a piecewise probability density function for perturbations. For the $K_l = 0$ equilibrium, this is a 0.5 probability of no perturbation, and a 0.5 probability of perturbed locations distributed uniformly between $K_l = 0$ and $K_h = 10$ (heavy black lines). For the $K_h = 10$ equilibrium there is a 0.5 probability of the same uniform distribution, but a 0.5 probability of no perturbations from $K_h = 10$ (heavy grey lines). For both of $K_l = 0$ and $K_h = 10$, perturbations are clustered around the originating equilibrium. The boundary point between basins of attraction is set at $K = 6$. As shown in Figure S1, a perturbation from $K_h = 10$ has a probability $P(K_{hh}) = 0.7$ of return to the high kelp equilibrium and a probability $P(K_{lh}) = 0.3$ of landing in $K_l = 0$'s basin of attraction and being absorbed to that equilibrium. When a catastrophic shift from a kelp forest equilibrium to a kelp depauperate equilibrium has occurred, there will also be a shift from the perturbation regime of the former to that of the latter. Once the shift to $K_l = 0$ has occurred, its probability density function governs perturbations. The probability of a perturbation from $K_l = 0$ ending up back at $K_h = 10$ is $P(K_{hl}) = 0.2$. The difference between $P(K_{hh}) = 0.7$ and $P(K_{hl}) = 0.2$ is due to the hysteresis associated with clustered perturbations. This exhibition of hysteresis, with the probability density function revealing clustering of displacement locations around the perturbation generating equilibrium (Paine et al., 1998; Uthicke et al., 2009), gives the two equilibria their own built-in inertia, and makes it less probable that a perturbation's displacement location will be in the kelp forest equilibrium's basin of attraction after a shift to a kelp depauperate regime has occurred. Clustered perturbations around the cryptic urchin and urchin barren equilibria may also occur, with hysteresis making a perturbation displacement location in the cryptic urchin equilibrium's basin of attraction less probable after the shift from a cryptic urchin equilibrium to an urchin barren has happened.

Local Stability

Local stability, unlike resilience, considers only one equilibrium at a time, and an equilibrium can be locally stable without being very resilient. Consider local stability conditions for the equilibria for (3) with $\alpha = 0.8$, $\beta = 0.08$, $\gamma = 0.26$, $\theta = 1$ and $S = 6$ (as in figure 2). There are three equilibria at $U_h = 7.4$, $U_b = 1.8$ and $U_l = 0.7$. With $U > 0$ The rate of growth in urchin density net of predation is (S1).

$$g = (\alpha - \beta U) - \frac{\gamma US}{(\theta + U^2)} = 0.8 - 0.08U - \frac{1.56U}{(1 + U^2)} \qquad \text{(S1)}$$

The derivative $\frac{dg}{dU}$ at an equilibrium will be negative for a stable equilibrium and positive for an unstable one.

$$\frac{dg}{dU} = -0.08 - \frac{1.56\left(1-U^2\right)}{\left(1+U^2\right)^2}$$ (S2)

At $U_h = 7.4$, $\frac{dg}{dU} = -0.05$ for a stable upper arm equilibrium. At $U_b = 1.8$, $\frac{dg}{dU} = 0.11$ for an

unstable middle arm equilibrium, and at $U_l = 0.7$, $\frac{dg}{dU} = -0.4$ for a stable lower arm

equilibrium.

   Sustainable Natural Capital

Sustainable natural capital refers to an ongoing ability to support marine ecosystem services that in turn support human life. A persistent kelp forest is an example. It is not only the kelp density of a kelp forest equilibrium that matters, but also its resilience probability and the resilience probabilities of other stable equilibria. Specifically, we define the sustainable natural capital of a cryptic urchin-kelp forest equilibrium (or another equilibrium like a kelp depauperate-urchin barren), from which pulse perturbations can be generated, as expected kelp density, the weighted sum of kelp densities at the post-perturbation equilibria. If there is only one round of perturbations from a cryptic urchin-kelp forest equilibrium, the weights are the transition probabilities, the cryptic urchin-kelp forest's resilience probability and the probabilities of shifts to other equilibria. If there are multiple perturbations, the expected kelp density of a kelp forest equilibrium will still depend on weighted kelp densities at the post perturbation equilibria, with the weights being Markov chains of probabilities. These probabilities reflect both the resilience of all the stable equilibria, and the presence or absence of hysteresis. A higher level of resilience for the kelp forest equilibrium will tend to produce set of weights that yield higher expected kelp density. In most cases, the original equilibrium influences the weights for at least the first few rounds of perturbations, but sooner or later they converge to steady state levels that are independent of the original equilibrium. The speed of convergence is inversely related to the degree of hysteresis. With the most extreme hysteresis, they never converge.

   Management Controls

The goal of management controls is to prevent losses in, or increase, sustainable natural capital, by maintaining, or restoring, the resilience of a kelp forest equilibrium (Scheffer et al., 2001; Beisner et al., 2003; Lessard et al., 2005; Mäler and Li, 2010). The literature has classified management controls in a number of ways. Systemic control implies reversing the cause of the problem and includes reduction in human harvesting of predators through restrictions on total allowable catch or marine protected areas (Grafton and Kompas, 2005; Ling et al., 2009; Ling and Johnson, 2012; Yates et al., 2019) . Reducing pollution, although sometimes not possible for technological or governance reasons, is also a systemic control (Islam and Tanaka, 2004). In contrast, symptomatic control implies using leverage points for more direct control of affected populations, urchin harvesting or culling, or kelp enhancement (seeding or transplantation) (Lessard et al., 2005).

A second distinction is between press controls and pulse controls (Scheffer et al., 2001; Suding et al., 2004). Press controls are ongoing responses to ongoing press changes like overharvesting or pollution. Pulse controls are temporary or intermittent responses to temporary or intermittent pulse perturbations, A third is the contrast between preventing catastrophic shifts from kelp forests to urchin barrens and reversing them to restore the original kelp forest equilibrium. Uncertainty is addressed though adaptive management that allows for learning while preserving the flexibility to make adjustments in controls in order to take advantage of new knowledge. Option value is the value generated by adaptive management (Holling, 1978; Dixit et al., 1994; Pindyck, 2007; McDonald-Madden et al., 2010; Sims et al., 2016; Layton et al., 2020).

Appendix B: Cases: Tasmania and Haida Gwaii

Kelp

Kelp, the foundation species of the kelp forest ecosystem, provides food and shelter for many species, and services to human society (Markel and Shurin, 2015; Levine et al., 2017; Small, 2018). Rich kelp forests typically exist with limited densities of cryptic urchins. While there are other factors such as pollution and storms that can affect kelp density (Foster and Schiel, 2010; Reed et al., 2011), urchins graze on kelp, and if the population growth of urchins is not checked by predators such as lobsters or sea otters, urchin density will explode and grazing will destroy kelp forests, leaving only kelp depauperate-urchin barrens.

There are two kinds of exogenous or metacommunity influences on kelp forest communities, temporary or pulse perturbations, and ongoing or press changes (Guzman et al., 2019). Natural variations driven by exogenous abiotic factors, such as storms or oscillations involving ocean currents, create pulse perturbations that can positively or negatively affect kelp forests or urchin populations (Petraitis and Dudgeon, 2004; Palumbi et al., 2008; Ling et al., 2009; Filbee-Dexter and Scheibling, 2012; Barboza, 2013; Filbee-Dexter and Wernberg, 2018). Diseases and/or population dynamics at other locations in the metacommunity can also cause pulses (Scheibling and Lauzon-Guay, 2010). Both kelp and urchin recruitment often rely on dispersal from elsewhere in the metacommunity (Guzman et al., 2019), and, with fluctuating transport mechanisms, these can be stochastic. Urchin recruitment is assisted by upwelling currents (Farrell et al., 1991), but mass mortalities may occur due to disease (Scheibling et al., 1999). Storms may destroy kelp forests, but turbulent water flow associated with storms that transport suspended kelp spores greater distances and promote kelp forest recovery (Reed et al., 1988).

Human caused changes can also be pulse perturbations, but often they tend to be press disturbances. Human overharvesting of the top predator is a press change, often implicated in kelp loss. Human activity is also culpable in ongoing eutrophication of coastal waters, and in pronounced and long-lasting changes in ocean currents, which lead to persistent ecosystem changes (Gorman et al., 2009; Muth et al., 2019; Qiu et al., 2019).

Tasmania

The two cases presented here are subject to both natural pulse perturbations and press anthropocentric changes. The first case comes from coastal Tasmania. In the Southwest Pacific, a

climate change related long term shift in the East Australian Current has resulted in an invasion of long-spined sea urchins to coastal Tasmania (Edgar et al., 2004). Although populations of endemic short-spined urchins (*Heliocidaris erythrogramma*) were already present, they are smaller and easier prey for southern rock/spiny lobster (*Jasus edwardsii*). Lobster predation, and a small commercial dive fishery for short-spined urchins, has limited their tendency to create barrens (Andrew, 1993; Ling et al., 2019). The influx of long spined urchins, starting in the 1970's, is causing areas along the northeastern coast of Tasmania to shift from kelp (*Ecklonia radiata* and *Phyllospora comosa*) dominated states to barrens (Ling et al., 2009; Johnson et al., 2011). While the spiny lobster is a predator, overfishing has reduced its density and size making it very difficult for the lobster predation to control urchin density. It has been suggested that both the press control reduced lobster harvest and the pulse control of urchin culling in incipient barrens may be needed to limit urchin barrens formation (Tracey et al., 2015).

Haida Gwaii

The second case is from Haida Gwaii, off the west coast of Canada, which, for some time, has had high urchin densities (*Mesocentrotus franciscanus* and *Strongylocentrotus purpuratus*) due to the absence of a strong urchin predator, the sea otter. Owing to the fur trade, the historical predators, sea otters, were extirpated from most of their geographic range, including Haida Gwaii, by the mid-1800s. Kelp has also declined (Estes and Palmisano, 1974; Estes and Duggins, 1995; Sloan and Bartier, 2000; Steneck et al., 2002; Estes et al., 2011; Ripple et al., 2016), and there have been declines in kelp habitat dependent species such as northern abalone *(Haliotis kamtschatkana)* and Pacific herring (*Clupea pallasii*) (Chadès et al., 2012). Following their reintroduction and protection, sea otters have returned to Vancouver Island and coastal British Columbia, but only very recently have there been any signs of recovery for Haida Gwaii (Estes and Palmisano, 1974; Estes et al., 1998; Fisheries and Oceans Canada, 2014; Lee et al., 2016; Lee et al., 2018; Gwaii Haanas Archipelago Management Board, 2020). With the expectation that sea the otter return is immanent, pulse urchin culling is being tried to restore kelp forests (Lee et al., 2016; Trebilco et al., 2016; Lee et al., 2018).

Appendix C: Extreme Clustering and No Clustering

With urchin density fixed, and the kelp forest as the post perturbation equilibrium, from (1) and (2), hysteresis is exhibited in the partial resilience zone if a perturbation returnins to the kelp forest equilibrium has a greater probability of having been perturbed from that equilibrium than from the kelp depauperate one, 1.e. if (S3) holds.

$$P\left(K_{h/h/U}\right)=\pi_h+\left(1-\pi_h\right)\frac{K_{h/U}-K_{b/U}}{K_{h/U}-K_{l/U}}>P\left(K_{h/l/U}\right)=1-\pi_l-\left(1-\pi_l\right)\frac{K_{b/U}-K_{l/U}}{K_{h/U}-K_{l/U}} \qquad (S3)$$

(S3) can be simplied to (S4).

$$\pi_l\left(K_{h/U}-K_{b/U}\right)+\pi_h\left(K_{b/U}-K_{l/U}\right)>0 \qquad (S4)$$

For the partial resilience zone, $K_{h/U} > K_{b/U}$ and $K_{b/U} > K_{l/U}$. So, (S4) holds and there is hysteretic memory if $\pi_h + \pi_l > 0$ holds.

With the post perturbation equilibrium being a kelp depauperate one, (1) and (2) give (S5) as the condition for hysteresis.

$$P\left(K_{l/l/U}\right) = \pi_l + \left(1-\pi_l\right)\frac{K_{b/U} - K_{l/U}}{K_{h/U} - K_{l/U}} > P\left(K_{l/h/U}\right) = 1-\pi_h - \left(1-\pi_h\right)\frac{K_{h/U} - K_{b/U}}{K_{h/U} - K_{l/U}} \qquad (S5)$$

Simplifying (S5) also gives (S4), so the condition for hysteretic memory is also $\pi_h + \pi_l > 0$.

Extreme clustering in (S3) and (S5) is given by $\pi_h = \pi_l = 1$, giving $P\left(K_{h/h/U}\right) = 1 > P\left(K_{h/l/U}\right) = 0$ for the kelp forest equilibrium, and $P\left(K_{l/l/U}\right) = 1 > P\left(K_{l/h/U}\right) = 0$ for the kelp depauperate equilibrium. $P\left(K_{h/h/U}\right)$ only jumps from one to zero if U becomes large enough, $U \geq 7.7$, to be outside the partial resilience zone such that the kelp forest equilibrium disappears. $P\left(K_{l/l/U}\right)$ jumps from one to zero when U becomes small enough, $U \leq 0.6$, to be outside the partial resilience zone such that the kelp depauperate equilbrium disappears.

No clustering in the partial resilience zone occurs when, $\pi_h = \pi_l = 0$. The outcome of a perturbation does not depend on the equilibrium from which it is perturbed, $P\left(K_{h/h/U}\right) = P\left(K_{h/l/U}\right)$, $P\left(K_{l/l/U}\right) = P\left(K_{l/h/U}\right)$. As U is increased from $U \leq 0.6$ at the perfectly resilient kelp-forest end of the partial resilience zone, to $U \geq 7.7$ at the perfectly resilient kelp-depauperate end, both $P\left(K_{h/h/U}\right)$ and $P\left(K_{l/l/U}\right)$ change gradually with their changes completely offsetting each other. The hysteresis is removed and the probability of ending up at a kelp forest/kelp depauperate equilibrium does not depend on whether the perturbing equilibrium was a kelp forest or a kelp depauperate equilibrium.

Hysteresis conditions for perturbations ending up at a cryptic urchin versus urchin barren equilibrium in (5) and (6) are similar to those for (1) and (2), with ω_l and ω_l replacing π_h and π_l.

Perturbation distribution functions and hysteresis for both urchin and kelp perturbations play an important role in determining the natural capital/expected kelp levels in the partial resilience zone. Here we consider the two polar cases, extreme clustering for both trophic interactions, and no clustering. With the extreme clustering case, $\pi_l = \pi_h = \omega_h = \omega_l = 1$, there are effectively no perturbations and the original equilibrium is also the final equilibrium. $Q\left(U_{h/h}^{S,\alpha}\right) = 1$,

$Q\left(U_{l/h}^{S,\alpha}\right) = 0$, $Q\left(U_{l/l}^{S,\alpha}\right) = 1$, $Q\left(U_{h/l}^{S,\alpha}\right) = 0$, $P\left(K_{h/h/U_h}^{S,\alpha}\right) = 1$ $P\left(K_{l/l/U_h}^{S,\alpha}\right) = 1$,

$P\left(K_{h/l/U_h}^{S,\alpha}\right)=0$, $P\left(K_{l/h/U_h}^{S,\alpha}\right)=0$ $P\left(K_{h/h/U_l}^{S,\alpha}\right)=1$, $P\left(K_{i/h/U_h}^{S,\alpha}\right)=0$ $P\left(K_{l/l/U_l}^{S,\alpha}\right)=1$, and $P\left(K_{h/l/U_h}^{S,\alpha}\right)=0$,

the matrix of transition probabilities in (10) becomes become (S6).

$$A = \begin{pmatrix} a_{KCKC} & a_{DCKC} & a_{DBKC} & a_{KBKC} \\ a_{KCDC} & a_{DCDC} & a_{DBDC} & a_{KBDC} \\ a_{KCDB} & a_{DCDB} & a_{DBDB} & a_{KBDB} \\ a_{KCKB} & a_{DCKB} & a_{DBKB} & a_{KBKB} \end{pmatrix} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix} \tag{S6}$$

Whichever of the equilibria is the starting point, there will nevet be any movement to another equilibrium. Expected kelp levels will always be at the starting point equilibrium level. Only when an equilbrium completely disappears will there be an inenvitable move to a new equilibrium. With $\alpha = 0.8$ and $S = 6$, either $U_l^{6,0.8} = 0.7$ or $U_h^{6,0.8} = 7.4$, and whichever of $K_{h/0.7}^{6,0.8} = 9.7$ $K_{l/0.7}^{6,0.8} = 0.06$, $K_{l/7.4}^{6,0.8} = 0.004$ or $K_{h/7.4}^{6,0.8} = 5.9$ is the initial equilibrium, will remain the equilibrium after one or many rounds of perturbations.

The other extreme case is that of no skewness, $\pi_l = \pi_h = \omega_h = \omega_l = 0$. The post-perturbation equilibrium does not depend on the pre-perturbation equilibrium, and $Q\left(U_{h/h}^{S,\alpha}\right) = Q\left(U_{h/l}^{S,\alpha}\right)$, $Q\left(U_{l/h}^{S,\alpha}\right) = Q\left(U_{l/l}^{S,\alpha}\right)$, $P\left(K_{h/h/U_h}^{S,\alpha}\right) = P\left(K_{h/l/U_h}^{S,\alpha}\right)$ $P\left(K_{l/l/U_h}^{S,\alpha}\right) = P\left(K_{l/h/U_h}^{S,\alpha}\right)$, $P\left(K_{h/h/U_l}^{S,\alpha}\right) = P\left(K_{h/l/U_l}^{S,\alpha}\right)$, and $P\left(K_{l/h/U_l}^{S,\alpha}\right) = P\left(K_{l/l/U_l}^{S,\alpha}\right)$. The transition probability matrix has identical rows, as in (S7). With $S = 6$ and $\alpha = 0.8$, the entries are as in the rightmost matrix.

$$A = \begin{pmatrix} a_{KCKC} & a_{DCKC} & a_{DBKC} & a_{KBKC} \\ a_{KCDC} & a_{DCDC} & a_{DBDC} & a_{KBDC} \\ a_{KCDB} & a_{DCDB} & a_{DBDB} & a_{KBDB} \\ a_{KCKB} & a_{DCKB} & a_{DBKB} & a_{KBKB} \end{pmatrix} = \begin{pmatrix} 0.198 & 0.002 & 0.272 & 0.528 \\ 0.198 & 0.002 & 0.272 & 0.528 \\ 0.198 & 0.002 & 0.272 & 0.528 \\ 0.198 & 0.002 & 0.272 & 0.528 \end{pmatrix} \tag{S7}$$

The starting point vector $\left(\Pi_{KC0}\ \Pi_{DC0}\ \Pi_{DB0}\ \Pi_{KB0}\right)$ gives a weight to each row in determining the probability of each outcome after one round of perturbations. Since all rows are the same, the probability of each outcome is the same regardless of the starting point vector. The weights sum to one giving (S8).

$$\left(\Pi_{KC1}\ \Pi_{DC1}\ \Pi_{DB1}\ \Pi_{KB1}\right) A = \left(0.198\ \ 0.002\ \ 0.272\ \ 0.528\right) \tag{S8}$$

After two rounds the resulting probabilities are the same, as shown in (S9).

$$\begin{aligned}\left(\Pi_{KC2}\ \Pi_{DC2}\ \Pi_{DB2}\ \Pi_{KB2}\right)A &= \left(0.198\ \ 0.002\ \ 0.272\ \ 0.528\right)A\\ &= \left(0.198\ \ 0.002\ \ 0.272\ \ 0.528\right)\end{aligned} \tag{S9}$$

The equilibrium probabilities are given by (S10).

$$\left(\Pi_{KC*}\ \Pi_{DC*}\ \Pi_{DB*}\ \Pi_{KB*}\right)A = \left(\Pi_{KC*}\ \Pi_{DC*}\ \Pi_{DB*}\ \Pi_{KB*}\right) = \left(0.198\ \ 0.002\ \ 0.272\ \ 0.528\right) \tag{S10}$$

The equilibrium expected kelp is given by (S11).

$$K_{E*}^{6,0.8} = \left(0.198\ \ 0.02\ \ 0.272\ \ 0.538\right)\begin{pmatrix}9.7\\0.06\\0.004\\5.9\end{pmatrix} = 5.1 \tag{S11}$$

With no hysteresis, the equilibrium transition probabilities and equilibrium expected kelp, which are independent of the original equilibrium, are reached immediately (after one perturbation) regardless of the original equilibrium. $K_{E*}^{6,0.8} = 5.1$ is different from the kelp densities at any original equilibrium (9.7, 0.06, 0.004 and 5.9) because there is not perfect resilience, but it is reached immedialtely by a perturbation from any of them because of the absence of hysteresis.

Appendix D: Tasmania Case, $a = 0.7$

In figure S2, with $S = 5.5$ and $a=0.7$ there are two sable urchin equilibria, $U_l^{5.5,0.7} = 0.64$ and $U_h^{5.5,0.7} = 5.7$, and an unstable equilibrium at $U_b^{5.5,0.7} = 2.4$. With a increasing from $\alpha = 0.42$ and $\omega_l = \omega_h = 0.5$, $U_l^{5.5,0.7} = 0.64$ will be the original equilibrium, and perturbations will cluster near that equilibrium, resulting in $Q\left(U_{l/l}^{5.5,0.7}\right) = 0.66$ and $Q\left(U_{h/l}^{5.5,0.7}\right) = 0.34$. If $U_h^{5.5,0.7} = 5.7$ was the original equilibrium with clustered perturbations, the result would have been $Q\left(U_{h/h}^{5.5,0.7}\right) = 0.84$ and $Q\left(U_{l/h}^{5.5,0.7}\right) = 0.16$. From figure S3, with $\pi_h = \pi_l = 0.5$, the high kelp equilibria would have be either $K_{h/0.64}^{5.5,0.7} = 9.75$ or $K_{h/5.7}^{5.5,0.7} == 7.5$ with return probabilities $P\left(K_{h/h/0.64}^{5.5,07}\right) = 0.99$ and $P\left(K_{h/h/5.7}^{5.5,07}\right) = 0.84$. The low kelp equilibria would have been either

$K_{1/0.64}^{5.5,0.7} = 0.075$ or $K_{1/5.7}^{5.5,0.7} = 0.005$, with return probabilities of $P\left(K_{1/1/0.64}^{5.5,07}\right) = 0.51$ and $P\left(K_{1/1/5.7}^{5.5,07}\right) = 0.66$.

Starting from the KC equilibrium, after one perturbation, the probabilities for ending up at each of the four equilibria are as shown in (S12).

$$\left(\Pi_{KC0} \quad \Pi_{DC0} \quad \Pi_{DB0} \quad \Pi_{KB0} \right) A$$

$$= \left(1 \; 0 \; 0 \; 0 \right) \begin{pmatrix} a_{KCKC} & a_{DCKC} & a_{DBKC} & a_{KBKC} \\ a_{KCDC} & a_{DCDC} & a_{DBDC} & a_{KBDC} \\ a_{KCDB} & a_{DCDB} & a_{DBDB} & a_{KBDB} \\ a_{KCKB} & a_{DCKB} & a_{DBKB} & a_{KBKB} \end{pmatrix}$$

$$= \left(1 \; 0 \; 0 \; 0 \right) \begin{pmatrix} 0.6534 & 0.0066 & 0.0544 & 0.2856 \\ 0.3234 & 0.3366 & 0.2244 & 0.1156 \\ 0.0784 & 0.0816 & 0.5544 & 0.2856 \\ 0.1584 & 0.0016 & 0.1344 & 0.7056 \end{pmatrix}$$

$$= \left(\Pi_{KC1} \quad \Pi_{DC1} \quad \Pi_{DB1} \quad \Pi_{KB1} \right) = \left(0.6534 \quad 0.0066 \quad 0.0544 \quad 0.2856 \right)$$

(S12)

The expected kelp level after one pertubations is (S13).

$$K_{EKC1}^{5.5,0.7} = \left(\Pi_{KC1} \quad \Pi_{DC1} \quad \Pi_{DB1} \quad \Pi_{KB1} \right) A \begin{pmatrix} K_{h/0.64}^{5.5,0.7} \\ K_{1/0.64}^{5.5,0.7} \\ K_{1/5.7}^{5.5,0.7} \\ K_{h/5.7}^{5.5,0.7} \end{pmatrix}$$

(S13)

$$= \left(0.6534 \quad 0.0066 \quad 0.0544 \quad 0.2856 \right) \begin{pmatrix} 9.75 \\ 0.075 \\ 0.005 \\ 7.5 \end{pmatrix} = 8.371$$

After two rounds of perturbations, we probabilities for the four equilibrium as given in (S14)

$$\left(\Pi_{KC3} \quad \Pi_{DC2} \quad \Pi_{DB2} \quad \Pi_{KB2} \right) = \left(\Pi_{KC1} \quad \Pi_{DC1} \quad \Pi_{DB1} \quad \Pi_{KB1} \right) A =$$

$$= \left(0.6534 \; 0.0066 \; 0.0544 \; 0.2856 \right) \begin{pmatrix} 0.6534 & 0.0066 & 0.0544 & 0.2856 \\ 0.3234 & 0.3366 & 0.2244 & 0.1156 \\ 0.0784 & 0.0816 & 0.5544 & 0.2856 \\ 0.1584 & 0.0016 & 0.1344 & 0.7056 \end{pmatrix}$$

(S14)

$$= \left(0.47857 \quad 0.01143 \quad 0.1056 \quad 0.4043 \right)$$

Expected kelp after two rounds is given by (S15).

$$K_{EFC2}^{5.5,0.7} = \begin{pmatrix} \Pi_{KC2} & \Pi_{DC2} & \Pi_{DB2} & \Pi_{KB2} \end{pmatrix} \begin{pmatrix} K_{h/0.64}^{5.5,0.7} \\ K_{1/0.64}^{5.5,0.7} \\ K_{1/5.7}^{5.5,0.7} \\ K_{h/5.7}^{5.5,0.7} \end{pmatrix}$$

(S15)

$$= \begin{pmatrix} 0.47857 & 0.01143 & 0.1056 & 0.4043 \end{pmatrix} \begin{pmatrix} 9.75 \\ 0.075 \\ 0.005 \\ 7.5 \end{pmatrix} = 7.707$$

The equilibrium outcome probability vector is

$\begin{pmatrix} \Pi_{KC*} & \Pi_{DC*} & \Pi_{D*B} & \Pi_{KB*} \end{pmatrix} A = \begin{pmatrix} \Pi_{KC*} & \Pi_{DC*} & \Pi_{D*B} & \Pi_{KB*} \end{pmatrix} = \begin{pmatrix} 0.29184 & 0.02816 & 0.19584 & 0.48416 \end{pmatrix}$,

giving an expected kelp level of $K_{ECC*}^{5.5,0.7} = 6.479$. Due to imperfect resilience and hysteresis,

$K_{h/0.64}^{5.5,0.7} = 9.75 > K_{EKC}^{5.5,0.7} = 8.371 > K_{EKC2}^{5.5,0.7} = 7.707 > K_{EKC*}^{5.5,0.7} = 6.497$.

Appendix E: Adaptive Management and Option Value: Monitoring Sea Otter Recovery

Uncertain knowledge with respect to sea otter recovery is modelled as a 0.5 probability that $S = 6$ is being approached, and a 0.5 probability that $S = 9$ is being approached. Since the investment in pulse culling and kelp enhancement must be made with current information, assume that $E(S) = 7.5$ is treated as if it is certain. Beginning from a DB equilibrium at $E(S) = 7.5$, there could be a return to DB or a displacement to one of two other equilibria, the KB or the perfectly resilient KC. Perfect resilience for KC implies there is no DC. This gives the three-by-three A matrix in (S16).

$$A = \begin{pmatrix} a_{KCKC} & a_{DBKC} & a_{KBKC} \\ a_{KCDB} & a_{DBDB} & a_{KBDB} \\ a_{KCKB} & a_{DBKB} & a_{KBKB} \end{pmatrix} = \begin{pmatrix} 0.76 & 0.046 & 0.194 \\ 0.26 & 0.599 & 0.141 \\ 0.26 & 0.141 & 0.599 \end{pmatrix}$$

(S16)

Starting from a DB, equilibrium probabilities, $\begin{pmatrix} \Pi_{KC0} & \Pi_{DB0} & \Pi_{KB0} \end{pmatrix} = \begin{pmatrix} 0 & 1 & 0 \end{pmatrix}$, and the middle row of A determine the outcomes after the first round of perturbations. If sufficient urchin culling is immediately undertaken, with no kelp enhancement required (because there is no DC), the transition matrix can be changed. Increasing a_{KCDB} from 0.26 to 1, changes the A matrix to A' in (S17).

$$A' = \begin{pmatrix} 0.76 & 0.046 & 0.194 \\ 1 & 0 & 0 \\ 0.26 & 0.141 & 0.599 \end{pmatrix} \quad (S17)$$

After one round of pulse urchin culling, the resulting outcome is $\left(\Pi_{KC1} \ \Pi_{DB1} \ \Pi_{KB1}\right) = \left(1 \ 0 \ 0\right)$ shown in (S18).

$$\left(0 \ 1 \ 0\right) A' = \left(1 \ 0 \ 0\right) \quad (S18)$$

Once the KC equilibrium is restored, it must be sustained. That requires a switch to preventative culling that changes the A' matrix to A'' (S19).

$$A'' = \begin{pmatrix} 1 & 0 & 0 \\ 0.26 & 0.599 & 0.141 \\ 0.26 & 0.141 & 0.599 \end{pmatrix} \quad (S19)$$

As long as preventative culling maintains A'', (S20) will hold, sustaining the equilibrium vector $\left(\Pi_{KC*} \ \Pi_{DB*} \ \Pi_{KB*}\right) = \left(1 \ 0 \ 0\right)$.

$$\left(1 \ 0 \ 0\right) A'' = \left(1 \ 0 \ 0\right) \quad (S20)$$

The cost of restoring and sustaining a kelp forest includes the cost of getting from DB to KC and the cost of staying there (preventing a move away from KC). Staying there is arbitrarily defined as staying there for $m = 5$ rounds. For both restoration and prevention, we use the same cost function for per round costs as in (19), (20), giving the cost function $C_S^R + mC_S^P = 0.5\left(C_{Sc}^R + mC_{Sc}^P + C_{Sn}^R + mC_{Sn}^P\right)$, but add a subscript, S, and assume certainty about the cost function and no discounting. The cost of getting to KC and staying there for $m = 5$ rounds, given a sea otter density of $S = E(S) = 7.5$, is given by (S21).

$$
\begin{aligned}
C_S^R + mC_S^P = C_{7.5}^R + 5C_{7.5}^P &= \left[3.03\left(1 - a_{KCDB}\right)^3 + 0.5\left(1 - a_{KCDB}\right)\right] \\
&+ 5\left[3.03\left(1 - a_{KCKC}\right)^3 + 0.5\left(1 - a_{KCKC}\right)\right] \\
&= \left[3.03\left(0.74^3\right) + 0.5\left(0.74\right)\right] + 5\left[3.03\left(0.24^3\right) + 0.5\left(0.24\right)\right] = 1.8673
\end{aligned}
\quad (S21)
$$

We treat L as the value of lost natural capital services for five rounds from remaining at a DB rather than investing in pulse urchin culling to ensure a move to a KC. If there is no culling, there will be lost services that will depend on the S outcome, L if $S=6$, and 0 if $S=9$. However,

since we do not know which loss will occur, it is treated an expect loss of $0.5L$. If pulse culling is undertaken, it will be based on $E(S) = 7.5$. In the event that $S = 9$ happens, the losses in natural capital services will be zero regardless of the culling effort. But, in the event of an $S = 6$ outcome, there will not be sufficient culling and enhancement to completely eliminate the loss, leaving an expected remaining loss of $0.5R$ over five rounds. The control choice when $E(S) = 7.5$ is based on minimizing the cost of control plus the remaining loss with, versus the no-action expected loss, or (S22).

$$C_{7.5}^{\min} = \min\left[C_{7.5}^R + 5C_{7.5}^p + 0.5R, 0.5L\right] = \min\left[1.8674 + 0.5R, 0.5L\right] \tag{S22}$$

Pulse culling is undertaken if $L - R \geq 3.7345$.

If there is monitoring of sea otter recovery, there will be a monitoring cost of W. But, before the culling and enhancement decision is taken, it will be known whether $S = 6$, in the partial resiliemce zone, or $S = 9$, a fully resilient KC, is being approached, and there will be a choice of more intensive pulse urchin culling or none. If it is known that $S = 6$ is being approached, the choice is to accept a loss of L, or incur cost, $C_S^R + mC_S^p = C_6^R + 5C_6^p$, of ensuring a kelp forest outcome with no remaining loss, $R = 0$. There is a restorative cost, C_6^R, associated with increasing a_{KCDB} from 0.049 in (10) to 1, and a preventative cost of $5C_6^p$ to ensure a_{KCKC} stays at 1 rather than 0.549 for $m = 5$ rounds. These give (S23) and (S24).

$$C_S^R + mC_S^p = C_6^R + 5C_6^p = \left[3.03\left(1 - a_{KCDB}\right)^3 + 0.5\left(1 - a_{KCDB}\right)\right]$$
$$+ 5\left[3.03\left(1 - a_{KCKCB}\right)^3 + 0.5\left(1 - a_{KCKC}\right)\right] \tag{S23}$$
$$= \left[3.03\left(0.951^3\right) + 0.5\left(0.951\right)\right] + 5\left[3.03\left(0.451^3\right) + 0.5\left(0.451\right)\right] = 4.5841$$

$$C_6^{\min} = \min\left[C_6^R + 5C_6^P, L\right] = \min\left[4.5841, L\right] \tag{S24}$$

Pulse culling is undertaken if $L \geq 4.5841$. If it is known that $S = 9$ is being approached, there is already a probability of one for a KC equilibrium, and no pulse urchin culling is required, for a cost of $C_9^{\min} = 0$. Since there is a 0.5 probability of each outcome, $S = 6$ or $S = 9$, the expected cost, including the recovery monitoring cost, W, is (S25).

$$E(C^{\min}) = W + 0.5C_6^{\min} + 0.5(0) = W + \min\left(2.292, 0.5L\right) \tag{S25}$$

The cost difference between knowing the sea otter recovery outcome versus knowing only that there is a fifty-fifty chance of $S = 6$ and $S = 9$, is the difference between (S22) and (S25), and is given by (S26). V in (S26) is the option value associated with knowing the sea otter density

outcome and being able to adapt pulse investments in urchin culling to accommodate this knowledge.

$$V = C_{7.5}^{\min} - E\left(C^{\min}\right) = \min\left(1.8674 + 0.5R, 0.5L\right) - W - \min\left(2.292, 0.5L\right) \qquad \text{(S26)}$$

The option value created by monitoring depends on uncertainty about the sea otter recovery level translating into uncertainty about whether pulse urchin culling and kelp enhancement are worthwhile. Since both are unnecessary when $S = 9$, it must be that they are deemed worthwhile when $S = 6$ ($4.584 \leq L$). If, in addition, $3.7348 + R > L$ in absence of recovery monitoring, no pulse culling based on $E(S) = 7.5$ will occur, at a cost of $0.5L$. With monitoring, the cost will be 4.584 for culling and enhancement when $S = 6$ and zero when $S = 9$ This generates $V = 0.5L - W - 2.292 \geq 0$, which is positive as long as W is not too large. There is value to knowing which of $S = 6$ or $S = 9$ is being approached because the less costly alternative of investment in culling and enhancement can be used when $S = 6$. If $3.7348 + R \leq L$ in absence of recovery monitoring, pulse culling based on $E(S) = 7.5$ will happen. With monitoring, the level of culling and enhancement effort can be adjusted to minimize the cost (including service loss) for $S = 6$ as opposed to that based on $E(S) = 7.5$, so it will also be true that $4.584 \leq 3.7348 + R$. This gives $V = 1.8674 + 0.5R - W - 2.292 \geq 0$, which is positive for smaller monitoring costs.

Knowing whether. $S = 6$ or $S = 9$ enables investment in culling and enhancement control to be tailored to the sea-otter recovery level, with the possibility of making that investment more cost effective and generating positive option value. Of course, there will be a cost, W, to monitoring sea-otter recovery. As long as that cost is not too great, recovery monitoring is worthwhile.

An alternative case, with $S > 11$ as the upper S outcome, would give $E(S) > 8$. With no better information on sea-otter recovery, $E(S) > 8$ would suggest a KC, with no need for pulse control to generate a probability increase. If the possible recovery outcomes had been a fifty-fifty chance of approaching either $S = 6$ or $S = 11$, the expected level of $E(S) = 8.5$ would indicated a fully resiliient KC, necesitating no pulse urchin culling or kelp enhancement control. Uncertainty about S leads to uncertainty about culling and enhancement investment, if $4.584 \leq L$ when $S = 6$. The potentially positive option value is (S27).

$$V = \min\left(C_{8.5}^{\min}\right) - E\left(C^{\min}\right) = \min\left(0 + 0.5L, 0.5L\right) - W - \min\left(2.292, 0.5L\right) = 0.5L - W - 2.292 \quad \text{(S27)}$$

It is the value of gaining the knowledge that $S = 6$ is being approached and being able to act to minimize costs (including service losses) based on that knowledge.

Appendix F: Related Ecological Modelling Literature

The models and the empirical assessments vary in how many trophic interactions they consider, and the modelling efforts differ with respect to the opportunities considered for alternative steady states and hysteresis.

Baskett and Salomon (2010) use an urchin-kelp model, to show that competition between kelp and crustose coralline algae (CCA), and facilitation of sea urchin recruitment by CCA, dampens any positive numerical responsive of urchin density to kelp density, and generate alternative stable states and hysteresis. Ling et al.(2015) have documented the strength of hysteresis in urchin-kelp systems globally, finding that the shift from kelp forest to urchin barrens occurs at an urchin biomass of about 700 g.m^{-2}, but the reverse shift requires a biomass below 70 g.m^{-2}. Rustici et al. (2017) developed a mathematical predators-urchin model to show that human harvesting of predator fish can be varied to move between alternative stable states of high versus low urchin density. They used a Holling type III predation function for fish predation on urchins and allowed urchin density to influence the growth of predator density. The TRITON (Temperate Reefs in Tasmania with Lobsters and Urchins) simulation model included the full lobster-urchin-kelp system. It treats only the lobster-urchin relationship as having the potential for hysteresis, with urchin grazing on kelp modelled as a linear relationship (Marzloff, 2012; Marzloff et al., 2013). Dunn et al. (2017) also model both the predator-urchin and urchin-kelp relationships, with nonlinearities in the predator-urchin relationship. They include size specific predation of lobsters on urchin (predation declines with urchin size), and a form of recruitment facilitation for urchins. They find that size specific predation, not recruitment facilitation, drives the shift between kelp and barrens states. Size specific predation is found in the empirical work of Ling et al. (2019) and Dunn and Hovel (2019). Ling et al. (2019) find the highest lobster predation to be on small urchins within kelp beds. Dunn and Hovel (Dunn and Hovel, 2019) similarly find the highest predation rates and density dependent predation on purple urchin within kelp beds, but lower and either inverse density dependent, or density independent, predation within barrens. Selkoe at al. (2015), using data from Estes et al. (1998) and Estes et al.(2010), considered empirical evidence for hysteresis in the predator (sea otter)-urchin system, finding a forward shift at an otter density of at least 12 otters km^{-2} and a reverse shift at a density of 6.3.

Figure S1: Probability density functions for perturbations: $f_l(K)$ for perturbation from K_l - heavy black lines, and $f_h(K)$ for perturbations from K_h -heavy gray.lines Dashed line is boundary between basins of attraction.

Figure S2: Predator-urchin subsystem isocline for $\alpha = 0.7$: The cubic equation for the $\dot{U} = 0$ isocline is $U^3 - 8.75U^2 + (1 + 3.25S)U - 8.75 = 0$. The arrows indicate movement away from equilibria on the unstable arm and toward equilibria on the stable arms.

Figure S3: Urchin-kelp subsystem isocline: The cubic equation for the $\dot{K} = 0$ isocline is $K^3 - 10K^2 + (0.01 + 3.25U)K - 0.1 = 0$. The arrows indicate movement away from equilibria on the unstable arm and toward equilibria on the stable arms. The (U, K) coordinates for the letters are: a- $(0.64, 9.75)$, b- $(0.64, 0.14)$, c- $(0.64, 0.075)$ and d- $(5.7, 0.005)$.

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