nature ecology & evolution
SUPPLEMENTARY INFORMATION
VOLUME: 1 | ARTICLE NUMBER: 0068

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# Rapid and direct recoveries of predators and prey through synchronized ecosystem management

Jameal F. Samhouri[1]*, Adrian C. Stier[2], Shannon M. Hennessey[3], Mark Novak[4], Benjamin S. Halpern[2,5,6] and Phillip S. Levin[1]

**Is this theory robust to different intrinsic productivity rates, exploitation histories, and other considerations?**

Many factors might influence our theoretical expectations, the most important of which relate to life history traits of the predator and prey[1,2] and intensity of historical exploitation levels[3,4]. To assess potential effects of these factors, we first use numerical simulation to evaluate which recovery strategy produces the shortest return time and most direct recoveries given different combinations of predator and prey productivity and three scenarios of historical exploitation: under-exploitation, sustainable-exploitation, and over-exploitation[1], such that exploited predator and prey densities prior to recovery were ~70%, ~30%, and ~20% of unexploited values, respectively.

We calculate the percent reduction in community return time obtained from the recovery strategy with the shortest value compared to that with the next shortest. Because predator-first recovery always minimizes community volatility to zero, we report the volatility obtained from the recovery strategy with the second smallest value. This quantity represents the percentage by which the maximum community density achieved during the transient period of recovery exceeds the unexploited equilibrium community density.

Synchronous recovery consistently exhibits the fastest community return times; in numerical simulations, synchronous recovery produces 70-90% faster community return times than the other strategies (Supplementary Figs. 1-2). Higher exploitation levels slightly diminish the relative benefit of synchronous recovery in terms of community return time: synchronous recovery produces ~90% faster returns times in the underexploitation scenarios but ~70% faster returns times in the over-exploitation scenarios (Supplementary Fig. 2). In any specific exploitation scenario, higher prey intrinsic productivity rates reduce differences in community return time among recovery strategies.

Predator-first recovery damps out high-amplitude transient dynamics most under all exploitation scenarios, causing this strategy to exhibit the most direct recoveries (Supplementary Figs. 1-2). The second best strategy for producing small values of community volatility is synchronous recovery, with values ranging from 0-32% and an average of 8% (Supplementary Fig. 2). There was one exception to this pattern, where predator-first and synchronous recovery both had zero community volatility: $Y = 500$, $a_X$=$a_Y = 0.03$, and $r_X = 0.8$. Community volatility was four-fold higher for the prey-first strategy than for the synchronous strategy in the underexploitation scenario, but fourteen-fold higher in the overexploitation scenario (Supplementary Fig. 1). In any specific exploitation scenario, higher prey intrinsic productivity rates reduce differences in community volatility among recovery strategies.

Beyond species' productivity rates and exploitation histories, in real exploited communities more species (that interact in many ways beyond predator-prey dynamics), temporal variation in parameter values, environmental stochasticity, stage or spatial structure within predator and prey populations, and the potential for hysteresis following dis-assembly[5] (especially due to predator-prey role reversals[6,7]) may all interact to affect expectations for recovery times and trajectories[8–10]. Our two-trophic level predator-prey model assumes these factors are not necessary to understand broad patterns of ecosystem recovery. Similarly, the social and economic costs associated with cessation of predator versus prey harvest are nuanced, requiring incorporation of discount rates and consideration of the optimal effort required to achieve pre-specified social goals[11–13]. Certainly, exploring the potential effects of additional complexities will be important extensions of the basic ideas introduced here. Yet, even with their inclusion, the large differences in our transient approximations of return time and volatility between synchronous and sequential recovery strategies suggest the results should be general.

## **Do analytical solutions of recovery correspond to numerical simulations?**

In addition to conducting numerical simulations of synchronous and sequential community recovery, we determine the equilibrium solutions to the model (Box 1) analytically using Mathematica v10. To make this analysis more tractable using Mathematica, we reformulate equation 2 as follows:

$$\frac{dP}{dt} = P\left[c\left(a_x X + a_y Y\right) - sP - d_P\right] - h_P P \qquad \text{(S1)}$$

In this formulation, *s* represents density-dependent losses due to food limitation or other factors related to prey densities and is equivalent to

$$s = \frac{c(a_X X + a_Y Y) - d_P}{K_P} \qquad \text{(S2)}$$

We determine the equilibrium densities of the predator and focal prey that allow for feasible fixed point coexistence in four situations, when: (i) both species are exploited ($h_X > 0$, $h_P > 0$) (state *E* in Supplementary Fig. 3), (ii) only the prey is exploited ($h_X > 0$, $h_P = 0$) (state *S* in Supplementary Fig. 3), (iii) only the predator is exploited ($h_X = 0$, $h_P > 0$) (state *S* in Supplementary Fig. 3), or (iv) neither species is exploited ($h_X = h_P = 0$) (state *R* in Supplementary Fig. 3; Supplementary Table 1). Situation (i) thus corresponds to a dis-assembled community at equilibrium that could recover from exploitation via synchronous recovery (situation (iv)) or sequential recovery (situation (ii) or (iii) followed by (iv)).

Because the three recovery scenarios are nested within these four situations, we examine how the community responds to changes in the per capita rates with which predator and prey are harvested. In addition, we conduct analyses to consider how increased intrinsic growth rate of the focal prey population (from $r_X = 1$ to $r_X = 5$) and increased availability of other prey (from $Y = 500$ to $Y = 1000$), which effectively increases intrinsic growth rate of the predator population, influence community responses under the three recovery strategies. All interpretations are predicated on the insight that a press perturbation from an exploited to an unexploited state can be interpreted as the decay of a pulse perturbation from an exploited state back to an unexploited state (Supplementary Fig. 3).

Specifically, we evaluate the characteristic return time to the unexploited state following an instantaneous cessation of harvest ($-1/\mathrm{Re}(\lambda_1)$), the analytical first-order analog to true return time in the numerical simulations presented in the main text[14] (Supplementary Fig. 3). To be conservative, we calculate return time assuming that zero time is spent in situations (ii) and (iii) during sequential recoveries. In addition, we determine the community's reactivity (the maximum possible growth rate of its transient response toward the unharvested state following a cessation or reduction of harvest[15]). Note that reactivity relates closely to the community volatility metric used in the main text, but differs in that it reflects a first-order approximation to the community's response to a perturbation (i.e. the sudden cessation or reduction of harvest) of any magnitude

(Supplementary Fig. 3). Both community response metrics can be compared across the three recovery strategies by examining their values for $h_P = h_X = 0$ (synchronous), $h_P = 0$ for any value of $h_X$ (predator-first), or $h_X = 0$ for any value of $h_P$ (prey-first).

In general, our analytical results corroborated those obtained via numerical simulations (Supplementary Fig. 4). As would be expected given our model, equilibrium densities of both the prey (Supplementary Fig. 4a) and the predator (Supplementary Fig. 4b) decline linearly with increasing per capita harvest rates, with higher harvest rates on the prey reducing the range of harvest rates on the predator that permit coexistence (cf. blue and red lines in Supplementary Fig. 4b). Higher intrinsic growth of the prey population increases equilibrium densities of both the prey and the predator, while greater abundance of other prey increases the equilibrium density of the predator and decreases the equilibrium density of the prey.

Analytical solutions confirm that synchronous recovery exhibits the shortest characteristic return times ($h_X = h_P = 0$, blue line intercept of y-axis in both Supplementary Figs. 4c-d), but whether predator-first recovery ($h_P=0$, blue line in Supplementary Fig. 4c) or prey-first recovery ($h_X=0$, blue line in Supplementary Fig. 4d) causes the second shortest characteristic return time depends on the harvest rate of the species still being exploited (with all other parameters at their baseline values). These results account for characteristic return times from equilibria reached when one or both species are harvested.

The conclusion that synchronous recovery has the shortest return time is unaffected by changing the intrinsic growth rate of the focal prey. Return time for synchronous recovery (corresponding to $h_P = h_X = 0$ in both Supplementary Figs. 4cd) is faster than that of predator-first recovery for both baseline and large $r_X$ because the intersection of the $h_P$ =0 isocline with the y-intercept (i.e., at $h_X$ =0) in Supplementary Fig. 4c is less than the return time of the $h_P$ =0 isocline for any non-zero value of $h_X$ in both cases. Similarly, return time for synchronous recovery is faster than that of prey-first recovery for both baseline and large $r_X$ because the intersection of the $h_X$ =0 isocline with the y-intercept (i.e. at $h_P$ =0) in Supplementary Fig. 4d is less than the return time of the $h_X$ =0 isocline for any non-zero value of $h_P$ in both cases.

Increasing the availability of other prey, however, allows prey-first recovery to become faster than synchronous or predator-first recovery in the special case where $r_X$ is small and $Y$ is large. This result can be observed by examining the intersection of the $h_X$ =0 isocline with the y-intercept (i.e., at $h_P$ =0) in Supplementary Fig. 4d, and noting that it is greater than the return time of the $h_X$ =0 isocline for any non-zero value of $h_P$. However, synchronous recovery is faster than prey-first recovery for large $r_X$ and large $Y$. Furthermore, return time for synchronous recovery (corresponding to $h_P = h_X = 0$ in both Supplementary Figs. 4cd) is faster than that of predator-first recovery for both baseline and large $Y$ because the intersection of the $h_P$ =0 isocline with the y-intercept (i.e., at $h_X$ =0) in Supplementary Fig. 4c is less than the return time of the $h_P$ =0 isocline for any non-zero value of $h_X$ in both cases.

With all other parameters at their baseline values, predator-first recovery exhibits the lowest reactivity levels for any feasible prey harvest rate and declines with increasing prey harvest rate (Supplementary Fig. 4e), whereas prey-first recovery generates the largest reactivity levels at any feasible predator harvest rate, and prey-first reactivity increases with predator harvest rate (Supplementary Fig. 4f). Synchronous recovery thus exhibits an intermediate level of reactivity (blue line intercept of y-axis in both Supplementary Fig. 3e-f). These conclusions are largely unaffected by changes in $r_X$ and $Y$, although there is a small region of parameter space where large $Y$ causes the reactivity of synchronous recovery to be smaller than either of the other two strategies (Supplementary Fig. 4e).

Our results may be understood more generally by considering the energy that is taken out of the system via harvest: the more energy in the system, the faster the characteristic return time and the larger the reactivity[16]. Because energy is already lost in the transfer from prey to predator, harvesting some fraction of predators (i.e., at some given per capita rate) will remove less overall energy from the system than the harvest of the same fraction of prey. Thus, predator-first recovery will always result in a less reactive system. The effect of predator-first recovery on the return time will depend on the per capita rate at which the prey are harvested. If the prey's per capita harvest rate is large (e.g., over-exploitation scenario) then a reduction (or cessation) in the harvesting of the predator population can have a larger impact on recovery rate than when the prey's per capita harvest rate is low.

**Are there drawbacks to synchronous versus sequential recovery?**

Synchronous and sequential recovery strategies will have different socioeconomic implications due to different timing and durations of reduced harvest opportunities. We compare the cumulative total, predator-only, and prey-only yields among the recovery strategies assuming predators and prey hold equal value per unit biomass. We find that the cumulative total yield and the cumulative yield of prey differ by 5% or less among the recovery strategies (Supplementary Fig. 5). In contrast, predator-first recovery produces a cumulative yield of predators that is ~30% higher than cumulative predator yield under the other two strategies (Supplementary Fig. 5). However, because the duration of exploitation varies among the three recovery strategies (Fig. 2), predator yields per unit time prior to cessation of harvest are equivalent among the three recovery strategies (Supplementary Fig. 5). Furthermore, prey yield per unit time is lower for predator-first recovery than for the other two strategies (Supplementary Fig. 5). Thus, the drawbacks of synchronous recovery in terms of foregone yields are less than or equal to those associated with the other two strategies. We note, however, that differences in the value of predator and prey species may lead to different inferences about the effectiveness of these alternative recovery strategies[17].

**How frequent is synchronous versus sequential community recovery in the real world?**

We assessed a comprehensive database of marine fisheries[3], focusing on exploited communities in which time-series of generalist predators and their prey were available, spanning time periods in which both were considered overexploited and had since recovered. We define a dis-assembled community as one in which two or more species, occupying different trophic levels and occurring in the same geographic region, had overlapping periods of depletion. Following Neubauer et al.[3], we classify a species (stock) as depleted when its biomass, $B$, is less than half of its maximum sustainable yield, $B_{MSY}$. Depletion periods are considered to overlap among species if $B<0.5B_{MSY}$ for both species for three or more consecutive years. We focus our analysis on the subset of dis-assembled communities (hereafter, case studies) in which higher- and lower-trophic level species have a documented predator-prey relationship (Supplementary Tables 2-3).

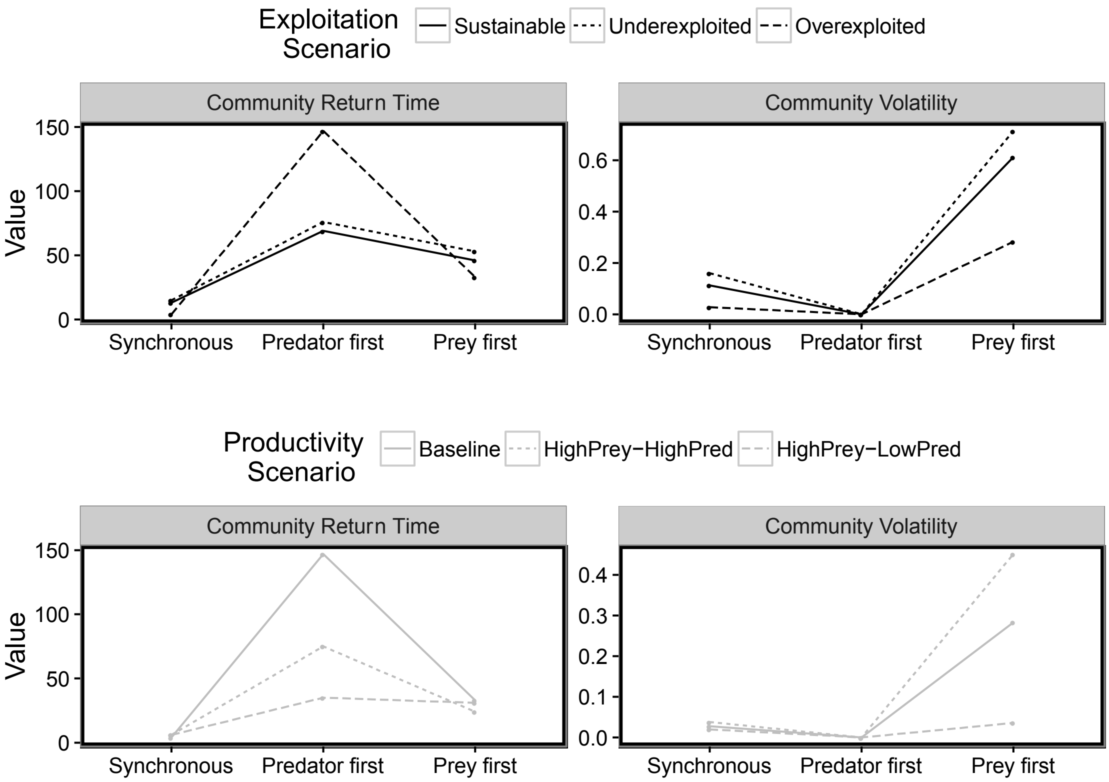
Within the case studies (*N*=37) we define a recovered community as one in which the biomass of both predator and prey meets or exceeds $B_{MSY}$, as inferred by Neubauer et al.[3]. We designate a case study as an example of synchronous recovery if recoveries occur within three years of one another, predator-first recovery if the predator recovers four or more years before the prey, and prey-first recovery if the prey recovers four or more years before the predator (Supplementary Table 2). Trophic levels for each species were obtained from FishBase and are considered distinct if they differ by 0.5 or more units. Note, however, that a trophic level distinction alone was insufficient for inclusion in our analysis; we restrict our analysis to communities with documented predator-prey relationships (Supplementary Table 3). Though this database precludes assessment of the influence of management actions, climate, or other factors in the observed recovery patterns, changes in exploitation rates were the primary factor under direct control of managers in these systems.

To test whether the decisions we made in categorizing case studies influence the outcomes of our analyses, we compare the results of the initial, moderately inclusive set of assumptions to two alternative sets of assumptions (Supplementary Table 2), and to removal of the most common species in the database, Atlantic cod (*N*=28). The first set of assumptions is the most inclusive of case studies in the database, and designates distinct trophic levels as a difference of 0.1 units or more, overlapping depletion periods as at least 1 year overlap, and synchronous recovery as the depletion period of both the predator and prey species ending in the same year. The second set of assumptions is the least inclusive of case studies in the database, and includes predators and prey with a trophic level difference greater than or equal to 1.0 with depletion periods overlapping by 5 years or more, and defines synchronous recovery as depletion periods that ended within 5 years of each other.

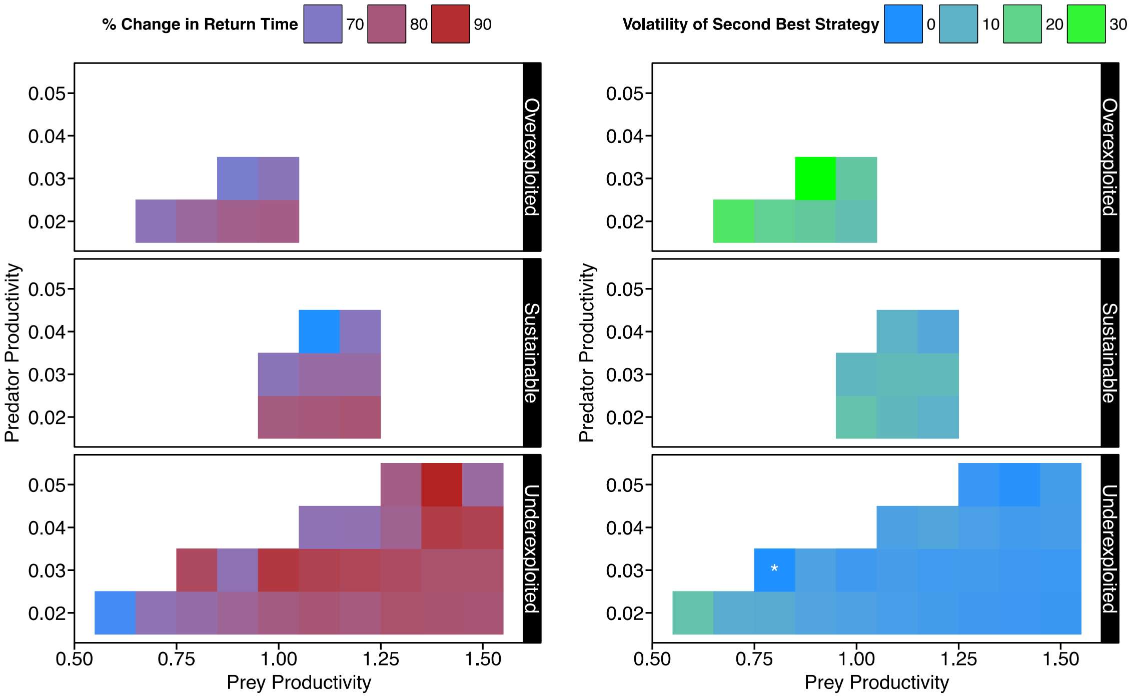
It is likely that some of the recoveries predicted by Neubauer et al. [3] did not, in fact, occur, especially for the most common species in the database, Atlantic cod. Our analysis would be more likely to classify these case studies as synchronous when, upon actual recovery of Atlantic cod, they would be more accurately assigned as sequential recoveries (with Atlantic cod recovering after its species pair). Thus, our test would conservatively favor the detection of synchronous recoveries. To determine the influence of Atlantic cod on our results, we repeat the Chi-squared tests removing these case studies.

Our assessment suggests that there are approximately equal numbers of synchronous and sequential recoveries, with predator-first recoveries being less common than prey-first recoveries ($N$=27 case studies; Supplementary Fig. 6). These patterns are generally robust to different ways of categorizing the case studies as synchronous versus sequential, and to the exclusion of the most common species from the database (Supplementary Figs. 7-8). The most inclusive set of assumptions leads to the conclusion that synchronous recovery is significantly less common than sequential recovery (chi-square test, $p$=0.004), while the least inclusive set leads to the opposite conclusion (chi-square test, $p$=0.09; Supplementary Fig. 7). However, neither of these alternative sets of assumptions changes the qualitative inference that predator-first recovery was least common (both chi-square tests, $p$<0.01; Supplementary Fig. 7). Finally, even with removal of case studies that include Atlantic cod from the analysis the number of occurrences of synchronous and sequential recoveries remains statistically indistinguishable (chi-square test, $p$=0.45), and this change makes the number of occurrences of synchronous, predator-first, and prey-first recoveries statistically indistinguishable as well (chi-square test, $p$=0.14; Supplementary Fig. 8).

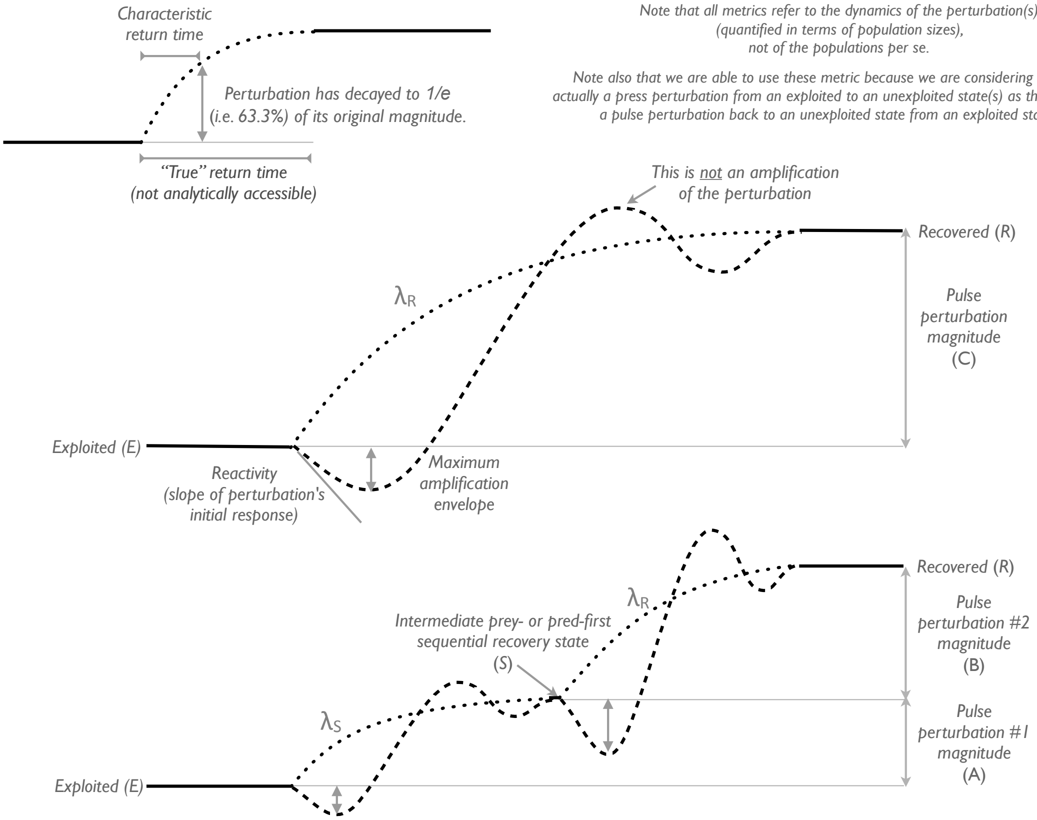
**Supplementary Figure 1.** Influence of alternative histories of exploitation (A,B) and different predator and prey intrinsic productivity rates (C,D) on the effectiveness of three recovery scenarios.



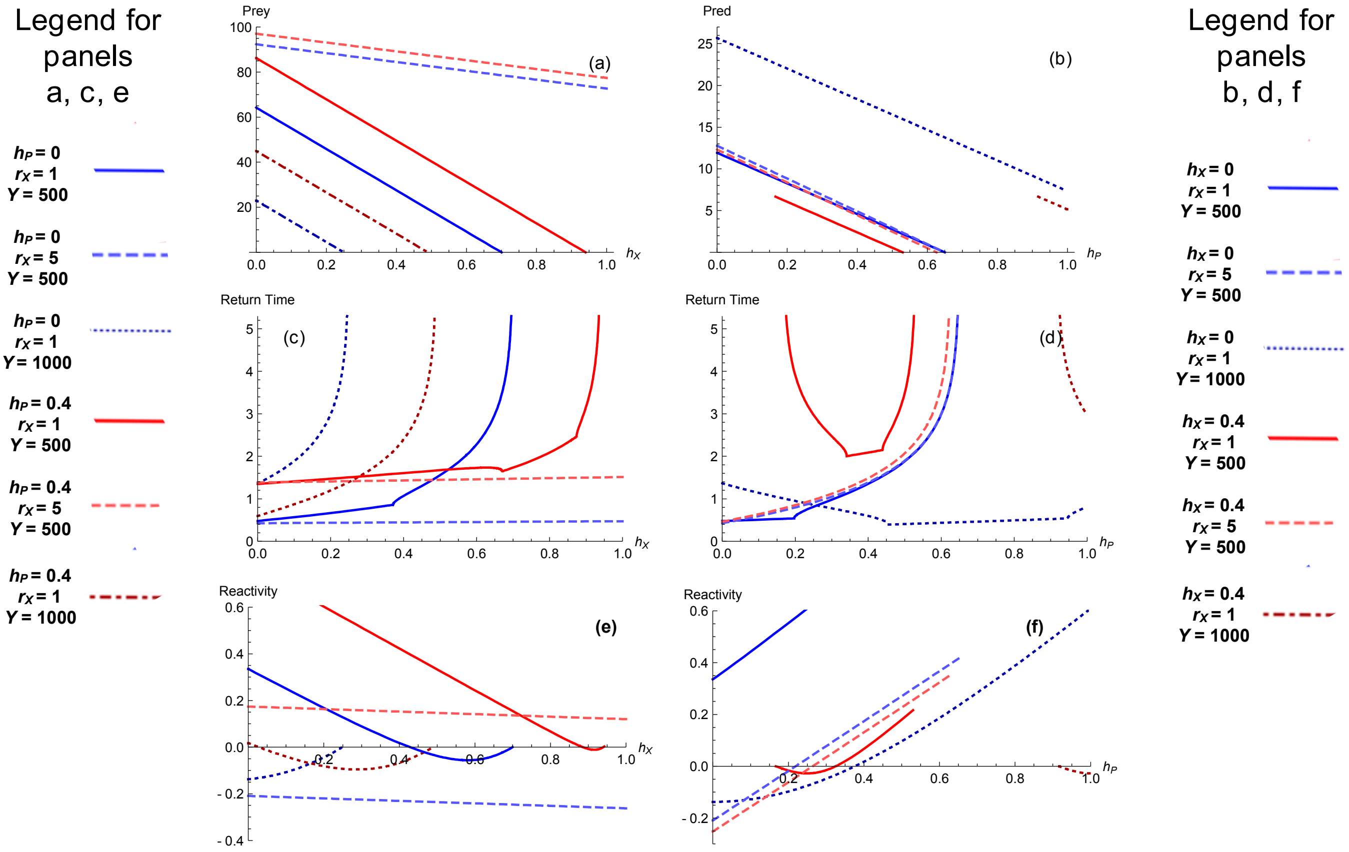
**Supplementary Figure 2.** Comparison of community (left) return times and (right) volatilities for a range of predator ($a_X$=$a_Y$) and prey ($r_X$) intrinsic productivity rates and across three exploitation scenarios. Community return times under synchronous recovery are compared to the next best strategy, while community volatilities are reported for the second best recovery strategy, as predator-first recovery always produces zero volatility. Blank cells represent parameter combinations that cannot lead to coexistence of predator and prey at under-, sustainably- and over-exploited levels.



**Supplementary Figure 3.** Let $E$, $S$, and $R$ respectively denote the equilibrium population sizes of the Exploited, intermediate step of the Sequential recovery (either prey- or predator-first), and the fully Recovered states. Let $A$ denote the difference in population size between $E$ and $S$, let $B$ denote the difference in population size between $S$ and $R$, and let $C$ denote the difference in population size between E and R. It must then be that $A + B = C$. Finally, let $\lambda_R$ be the return rate to the Recovered state following a pulse perturbation, regardless of how large the perturbation is (i.e., whether the perturbation takes the system all the way to Exploited $E$ state or back to the intermediate $S$ state). Also let $\lambda_S$ be the return rate to the intermediate Sequential recovery state (either prey- or predator-first). To be conservative, we calculate return time assuming that zero time is spent in the Sequential recovery state $S$. See SI text for details.

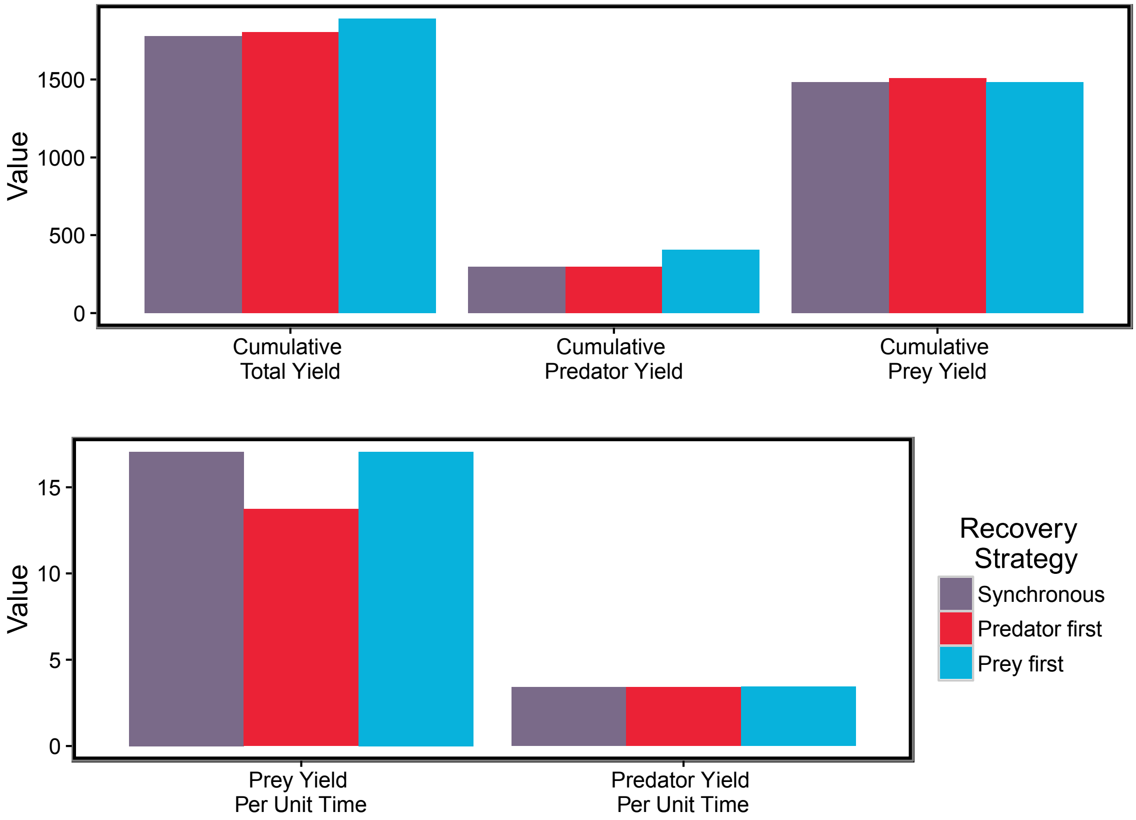


**Supplementary Figure 4.** Analytical solutions for the (a-b) equilibrium densities, (c-d) characteristic return times, and (e-f) reactivities of the community as a function of per capita harvest rates on the prey and predator.  Lines are drawn only within parameter ranges allowing feasible fixed-point coexistence, with solid lines corresponding to baseline parameter set. Note that given our baseline parameter set, coexistence is not stable and feasible for $Y < 350$. The *y*-intercepts in the figures correspond to solutions for synchronous recovery ($h_X = h_P = 0$). Blue lines indicate solutions for $h_P = 0$ (predator-first recovery) in (a), (c), and (e), and for $h_X = 0$ (prey-first recovery) in (b), (d), and (f). Red lines indicate solutions for $h_P = 0.4$ in (a), (c), and (e), for $h_X = 0.8$ in (b), (d), and (f). In all panels, dashed lines indicate solutions for focal prey's intrinsic growth rate increased 5-fold above baseline (i.e. from $r_X = 1$ to $r_X = 5$), whereas dotted lines indicate solutions for other prey's abundance increased 2-fold above baseline (i.e., from $Y = 500$ to $= 1000$). See Supplementary Information text for details, and *Methods* in the main text for other parameter values.

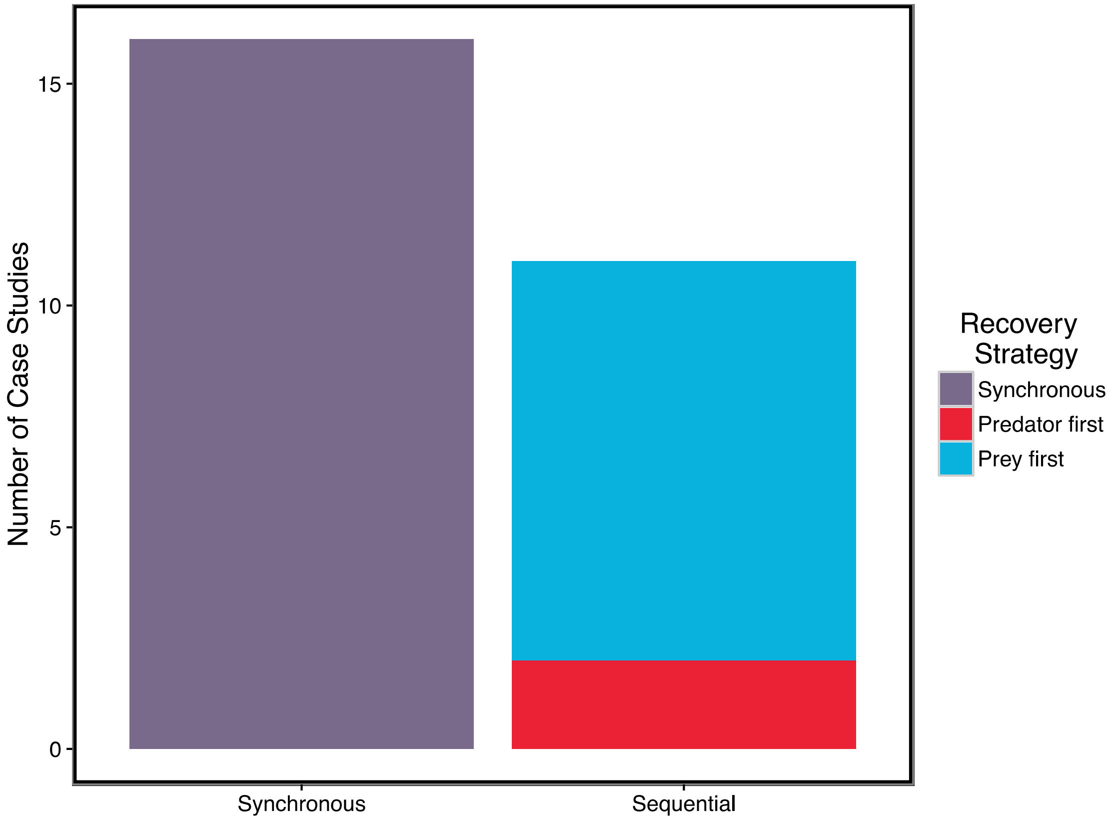

Legend for panels a, c, e
hP = 0 rX = 1 Y = 500
hP = 0 rX = 5 Y = 500
hP = 0 rX = 1 Y = 1000
hP = 0.4 rX = 1 Y = 500
hP = 0.4 rX = 5 Y = 500
hP = 0.4 rX = 1 Y = 1000
Prey
(a)
100
80
60
40
20
0.0
0.2
0.4
0.6
0.8
1.0
hX
Pred
(b)
25
20
15
10
5
0.0
0.2
0.4
0.6
0.8
1.0
hP
Return Time
(c)
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
hX
Return Time
(d)
5
4
3
2
1
0
0.0
0.2
0.4
0.6
0.8
1.0
hP
Reactivity
(e)
0.6
0.4
0.2
0.0
- 0.2
- 0.4
0.2
0.4
0.6
0.8
1.0
hX
Reactivity
(f)
0.6
0.4
0.2
0.0
- 0.2
0.2
0.4
0.6
0.8
1.0
hP
Legend for panels b, d, f
hX = 0 rX = 1 Y = 500
hX = 0 rX = 5 Y = 500
hX = 0 rX = 1 Y = 1000
hX = 0.4 rX = 1 Y = 500
hX = 0.4 rX = 5 Y = 500
hX = 0.4 rX = 1 Y = 1000

272 **Supplementary Figure 5.** Effect of three recovery scenarios under the baseline

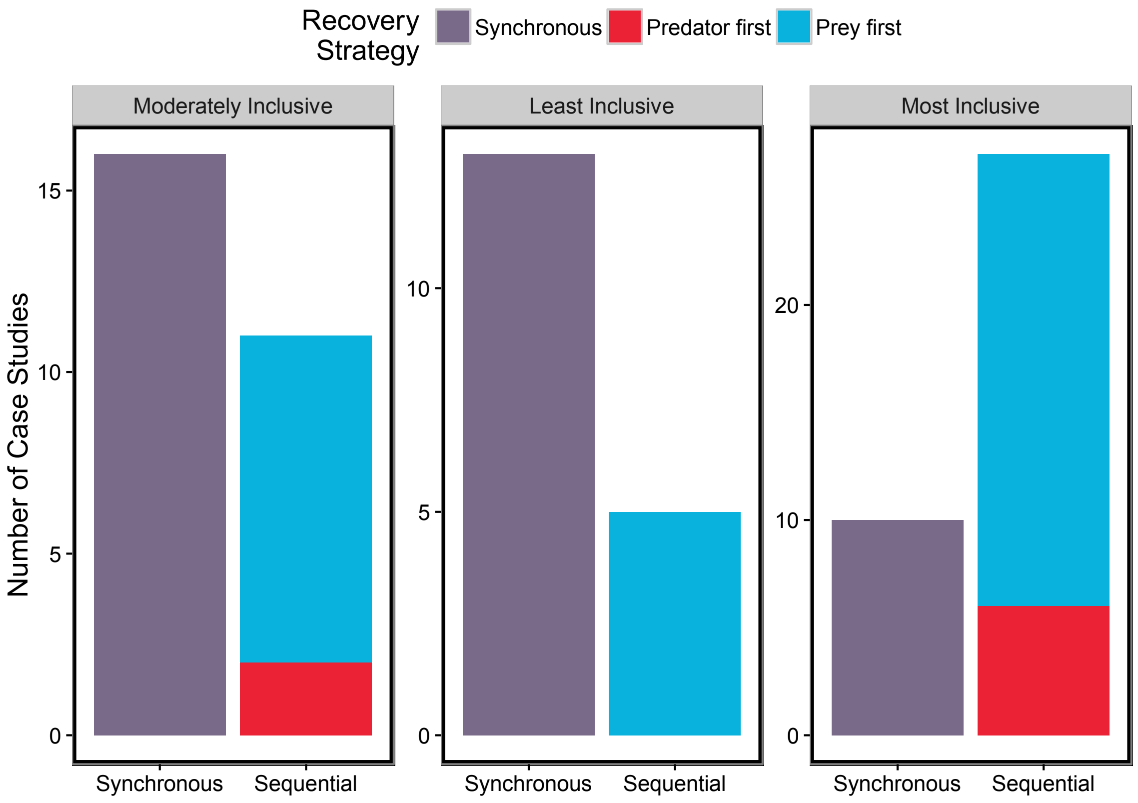
273 parameter set on (top) cumulative yields and (bottom) yields per unit time.



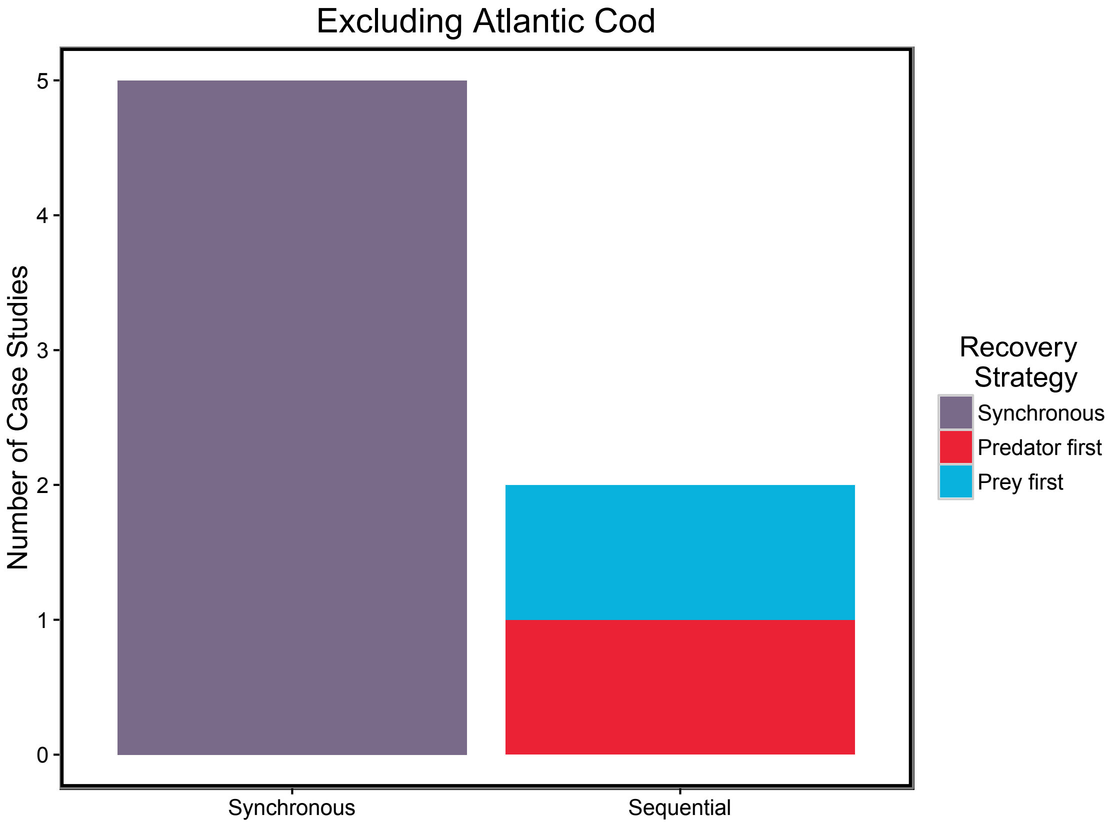
**Supplementary Figure 6.** Frequency of synchronous vs sequential recoveries (chi-square test: $p$=0.46) and synchronous ($N$=16), predator-first ($N$=2), and prey-first ($N$=9) recoveries (chi-square test: $p$=0.004), identified in the RAM legacy database[3].



**Supplementary Figure 7**. Frequency of synchronous vs sequential recoveries, and synchronous, predator-first, and prey-first recoveries, identified in the RAM legacy database[3]. Left, the moderately inclusive categorization, such that overlapping depletion periods of predator and prey were defined as 3+ years, trophic level distinctions were defined as ≥0.5 TL unit difference, and synchronous recoveries were identified as those that occurred within 3 years of one another. Middle, the least inclusive categorization (synchronous *N*=13, predator-first *N*=0, prey-first *N*=5), such that overlapping depletion periods of predator and prey were defined as 5+ years, trophic level distinctions were defined as ≥1 TL unit difference, and synchronous recoveries were identified as those that occurred within 5 years of one another. Right, the most inclusive categorization (synchronous *N*=10, predator-first *N*=6, prey-first *N*=21), such that overlapping depletion periods of predator and prey were defined as 1+ years, trophic level distinctions were defined as ≥0 TL unit difference, and synchronous recoveries were identified as those that occurred in the same year.



**Supplementary Figure 8.** Frequency of synchronous vs sequential recoveries, and synchronous (*N*=5), predator-first (*N*=1), and prey-first (*N*=1) recoveries, identified in the RAM legacy database[3], after removing Atlantic cod from the case studies.



**Supplementary Table 1.** Steady state analytical solutions under exploited and three recovery scenarios.

| Equilbrium | Prey | Predator |
|---|---|---|
| Exploited | $\frac{((-\mathrm{hX}+r)s+a(d+\mathrm{hP}-acY))K}{rs+a^2cK}$ | $\frac{-r(d+\mathrm{hP}-acY)+ac(-\mathrm{hX}+r)K}{rs+a^2cK}$ |
| Synchronous | $\frac{(rs+a(d-acY))K}{rs+a^2cK}$ | $\frac{r(-d+ac(Y+K))}{rs+a^2cK}$ |
| Prey-first | $\frac{(rs+a(d+\mathrm{hP}-acY))K}{rs+a^2cK}$ | $-\frac{r(d+\mathrm{hP}-ac(Y+K))}{rs+a^2cK}$ |
| Predator-first | $\frac{((-\mathrm{hX}+r)s+a(d-acY))K}{rs+a^2cK}$ | $\frac{-dr+ac(-\mathrm{hX}K+r(Y+K))}{rs+a^2cK}$ |

**Supplementary Table 2.** Case studies extracted from Neubauer et al.[3] for empirical analysis.

| Region | Country | Predator | Prey | Predator Depletion period | Prey Depletion period | Depletion period overlap | Recovery strategy (moderate) | Recovery strategy (least) | Recovery strategy (most) |
|---|---|---|---|---|---|---|---|---|---|
| Baltic Area 30 (ICES) | Multinational | Atlantic cod | Herring | 1966-1982 | 1979-1989 | 3 | Predator-first | Predator-first | - |
| Baltic Area 31 (ICES) | Multinational | Atlantic cod | Herring | 1987-2011 | 1994-2007 | 13 | Prey-first | Prey-first | Synchronous |
| Baltic Areas 22 and 24 | Multinational | Atlantic cod | Sprat | 1986-2012 | 1986-1992 | 6 | Prey-first | Prey-first | Prey-first |
| Baltic Areas 25-32 | Multinational | Atlantic cod | Herring | 1987-2011 | 1996-2011 | 15 | Synchronous | Synchronous | Synchronous |
| Baltic Areas 25-32 | Multinational | Atlantic cod | Sprat | 1966-1982 | 1979-1983 | 3 | Synchronous | Predator-first | - |
| Baltic Areas 25-32 | Multinational | Atlantic cod | Sprat | 1987-2011 | 1986-1992 | 5 | Prey-first | Prey-first | Prey-first |
| Faroe Plateau | Multinational | Atlantic cod | Haddock | 1990-1995 | 1991-1996 | 4 | - | Predator-first | - |
| Faroe Plateau | Multinational | Atlantic cod | Haddock | 2004-2012 | 2008-2011 | 3 | - | Prey-first | - |
| FO 3LN | Multinational | Greenland halibut | Redfish species | 1995-2007 | 1992-2000 | 5 | Prey-first | Prey-first | - |
| FO 3N | Multinational | Atlantic cod | American Plaice | 1960-2008 | 1986-2008 | 22 | Synchronous | Synchronous | - |
| FO 3NO | Multinational | Atlantic cod | Redfish species | 1960-2008 | 1992-2000 | 8 | Prey-first | Prey-first | - |
| FO 3NO | Multinational | Atlantic cod | Yellowtail Flounder | 1960-2008 | 1976-1999 | 23 | Prey-first | Prey-first | Prey-first |
| FO 5Y | USA | Atlantic Halibut | Witch Flounder | 1890-2008 | 1994-2008 | 14 | Synchronous | Synchronous | Synchronous |
| FO 5YZ | USA | Atlantic Halibut | American Plaice | 1890-2008 | 1986-2008 | 22 | Synchronous | Synchronous | - |
| FO 5Z | USA | Atlantic Halibut | Winter Flounder | 1890-2008 | 1985-2007 | 22 | Synchronous | Prey-first | Synchronous |
| FO 5Zjm | Canada | Atlantic cod | Haddock | 1993-2004 | 1970-2002 | 9 | - | Prey-first | - |
| Georges Bank | USA | Atlantic cod | Acadian redfish | 1984-2008 | 1957-2008 | 24 | Synchronous | Synchronous | Synchronous |
| Georges Bank | USA | Atlantic cod | Haddock | 1984-2008 | 1968-2006 | 22 | - | Prey-first | - |
| Georges Bank | USA | Atlantic cod | White hake | 1984-2008 | 1994-2008 | 14 | - | Synchronous | - |
| Georges Bank | USA | Atlantic cod | Yellowtail Flounder | 1984-2008 | 1974-2008 | 24 | Synchronous | Synchronous | Synchronous |
| Gulf of Maine | USA | Atlantic cod | Northern shrimp | 1983-2008 | 1998-2006 | 8 | Synchronous | Prey-first | Synchronous |

| **Region** | **Country** | **Predator** | **Prey** | **Predator Depletion period** | **Prey Depletion period** | **Depletion period overlap** | **Recovery strategy (moderate)** | **Recovery strategy (least)** | **Recovery strategy (most)** |
|---|---|---|---|---|---|---|---|---|---|
| Gulf of Maine | USA | Atlantic cod | Yellowtail Flounder | 1983-2008 | 1985-2008 | 23 | Synchronous | Synchronous | Synchronous |
| Iceland | Multinational | Atlantic cod | Capelin | 1991-2012 | 2005-2007 | 2 | - | Prey-first | - |
| Iceland | Multinational | Atlantic cod | Haddock | 1991-2012 | 1983-2012 | 21 | - | Synchronous | - |
| Iceland | Multinational | Atlantic cod | Herring | 1991-2012 | 1989-2011 | 20 | Synchronous | Prey-first | Synchronous |
| Iceland | Multinational | Haddock | Capelin | 1983-2012 | 2005-2007 | 2 | - | Prey-first | - |
| Iceland | Multinational | Haddock | Capelin | 1983-2012 | 1980-1984 | 1 | - | Prey-first | - |
| Irish Sea | Multinational | Atlantic cod | European Plaice | 1978-2011 | 1995-2006 | 11 | Prey-first | Prey-first | Prey-first |
| Irish Sea | Multinational | Atlantic cod | European Plaice | 1978-2011 | 1976-1988 | 10 | Prey-first | Prey-first | Synchronous |
| Irish Sea (Northern) | Multinational | Atlantic cod | Herring | 1978-2011 | 1978-2011 | 33 | Synchronous | Synchronous | Synchronous |
| North Sea | Multinational | Atlantic cod | Herring | 1989-2011 | 1996-2002 | 6 | Prey-first | Prey-first | Prey-first |
| North Sea | Multinational | Atlantic cod | Norway pout | 1989-2011 | 2003-2008 | 5 | Synchronous | Prey-first | Synchronous |
| North Sea | Multinational | Atlantic cod | Sandeel | 1989-2011 | 2003-2008 | 5 | Synchronous | Prey-first | Synchronous |
| Northeast Arctic | Multinational | Atlantic cod | Haddock | 1979-2009 | 1977-1993 | 14 | - | Prey-first | - |
| Prince Rupert District | Canada | Sablefish | Pacific herring | 1997-2005 | 1966-2008 | 8 | Synchronous | Predator-first | - |
| Queen Charlotte Islands | Canada | Sablefish | Pacific herring | 1997-2005 | 1986-2008 | 8 | Synchronous | Predator-first | - |
| West Coast of Vancouver Island | Canada | Pacific cod | Pacific herring | 1994-2002 | 1995-2008 | 7 | Predator-first | Predator-first | - |

**Supplementary Table 3.** Documentation of predator-prey relationships analyzed for the case studies extracted from Neubauer et al.[3]. Note that we included only those predator-prey relationships for which there was documented evidence that the prey constituted 5% or more of the predator's diet.

| Region | Predator | Prey | Predator-prey relationship | Predator diet citation |
|---|---|---|---|---|
| Georges Bank | Atlantic cod | Acadian redfish | Redfish comprise 14% diet composition in cod stomachs near the Gulf of St. Lawrence (Kohler and Fitzgerald 1969), and while small redfish can make up <1% of cod diet by mass in the southern Gulf of St. Lawrence (Hanson and Chouinard 2002), cod over 50 cm near the Flemish Cap contained ~95% small redfish (Templeman 1965). | Hanson, J.M. and Chouinard, G.A. 2002. Diet of Atlantic cod in the southern Gulf of St Lawrence as an index of ecosystem change, 1959–2000. Journal of Fish Biology 60: 902–922.<br>Kohler, A.C., and Fitzgerald, D.N. 1969. Comparisons of Food of Cod and Haddock in the Gulf of St. Lawrence and on the Nova Scotia Banks. Journal Fisheries Research Board of Canada 26(5): 1273-1287.<br>Templeman, W. 1965. Some instances of cod and haddock behavior and concentrations in the Newfoundland and Labrador areas in relation to food. ICNAF Special Publication 6: 449-461. |
| | | | | |
| FO 3N | Atlantic cod | American Plaice | American Plaice are from 6% (Hanson and Chouinard 2002) to 27% (Waiwood and Majkowski 1984) composition in cod stomachs in the southern Gulf of St. Lawrence; 37% of cod over 100 cm in length contained some plaice (highest predation on small plaice; | Hanson, J.M. and Chouinard, G.A. 2002. Diet of Atlantic cod in the southern Gulf of St Lawrence as an index of ecosystem change, 1959–2000. Journal of Fish Biology 60: 902–922.<br>Powles, P.M. 1958a. Life history and ecology of American plaice (Hippoglossoides platessoides F.) in the |

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| | | | Powles 1958a). | Magdalen Shallows. Journal Fisheries Research Board of Canada 22(2):565-598.<br>Waiwood, K. and Majkowski, J. 1984. Food consumption and diet composition of cod, Gadus morhua, inhabiting the southwestern Gulf of St. Lawrence. Environmental Biology of Fishes Vol II 1:63-78. |
| | | | | |
| Iceland | Atlantic cod | Capelin | Atlantic cod consume a mean of 27.1% (peak 40%) of capelin in their diet (by weight; primary fish prey) in Iceland. | Jaworski, A. and Ragnarsson, S.A. 2006. Feeding habits of demersal fish in Icelandic waters: a multivariate approach. ICES Journal of Marine Science 63: 1682-1694. |
| | | | | |
| Irish Sea | Atlantic cod | European Plaice | European Plaice comprise from 2% (Mackinson and Daskalov 2007) to 20% (Daan 1973) of cod diet by weight in the North Sea. | Daan, N. 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Netherlands Journal of Sea Research 6 (4): 479–517.<br>Mackinson, S. and Daskalov, G, 2007. An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: description and parameterisation. Sci. Ser. Tech Rep., Cefas Lowestoft, 142: 196pp. |
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|---|---|---|---|---|
| Faroe Plateau; George's Bank (FO 5Zjm); Iceland; NE Arctic | Atlantic cod | Haddock | Haddock of all sizes make up 25-40% of cod diet in North Sea (Daan 1973), and approximately 9% in the Gulf of St. Lawrence (Kohler and Fitzgerald 1969). | Daan, N. 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Netherlands Journal of Sea Research 6 (4): 479–517.<br>Kohler, A.C., and Fitzgerald, D.N. 1969. Comparisons of Food of Cod and Haddock in the Gulf of St. Lawrence and on the Nova Scotia Banks. Journal Fisheries Research Board of Canada 26(5): 1273-128. |
| | | | | |
| Baltic Area 30, 31 (ICES); Baltic Areas 25-32; Iceland; Northern Irish Sea; North Sea | Atlantic cod | Herring | Cod have from 2-15% herring in their diet in the North Sea (Daan 1973). | Daan, N. 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Netherlands Journal of Sea Research 6 (4): 479–517. |
| | | | | |
| Gulf of Maine | Atlantic cod | Northern shrimp | Northern shrimp make up around 20% of cod diet, across size classes (Hanson and Chouinard 2002). | Hanson, J.M. and Chouinard, G.A. 2002. Diet of Atlantic cod in the southern Gulf of St Lawrence as an index of ecosystem change, 1959–2000. Journal of Fish Biology 60: 902–922. |
| | | | | |
| North Sea | Atlantic cod | Norway pout | Norway pout comprise 6.7% of Atlantic cod diet in the North sea (Mackinson and Daskalov 2007). | Mackinson, S. and Daskalov, G, 2007. An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: description and parameterisation. Sci. Ser. Tech Rep., Cefas Lowestoft, 142: 196pp. |
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|---|---|---|---|---|
| FO 3NO | Atlantic cod | Redfish species | Redfish (all sizes) comprise 14% diet composition in cod stomachs near the Gulf of St. Lawrence (Kohler and Fitzgerald 1969), and while small redfish can make up <1% of cod diet by mass in the southern Gulf of St. Lawrence (Hanson and Chouinard 2002), cod over 50 cm near the Flemish Cap contained ~95% small redfish (Templeman 1965). | Hanson, J.M. and Chouinard, G.A. 2002. Diet of Atlantic cod in the southern Gulf of St Lawrence as an index of ecosystem change, 1959–2000. Journal of Fish Biology 60: 902–922<br>Kohler, A.C., and Fitzgerald, D.N. 1969. Comparisons of Food of Cod and Haddock in the Gulf of St. Lawrence and on the Nova Scotia Banks. Journal Fisheries Research Board of Canada 26(5): 1273-1287.<br>Templeman, W. 1965. Some instances of cod and haddock behavior and concentrations in the Newfoundland and Labrador areas in relation to food. ICNAF Special Publication 6: 449-461. |
| | | | | |
| North Sea | Atlantic cod | Sandeel | Sandeel can make up from 5% (Mackinson and Daskalov 2007) to 10% of adult cod diet by weight (Daan 1973). | Daan, N. 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Netherlands Journal of Sea Research 6 (4): 479–517.<br>Mackinson, S. and Daskalov, G, 2007. An ecosystem model of the North Sea to support an ecosystem approach to fisheries management: description and parameterisation. Sci. Ser. Tech Rep., Cefas Lowestoft, 142: 196pp. |
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| Baltic Areas 22 and 24; Baltic Areas 25-32 | Atlantic cod | Sprat | Sprat in cod diet can reach 20% by weight in the North Sea (Daan 1973). | Daan, N. 1973. A quantitative analysis of the food intake of North Sea cod, *Gadus morhua*. Netherlands Journal of Sea Research 6 (4): 479–517. |
| | | | | |
| Georges Bank | Atlantic cod | White hake | White hake, all sizes, can make up 5% of cod over 60cm diet (Powles 1958b) or from 1-19% volume in stomachs of cod greater than 30cm in the Gulf of St. Lawrence. | Powles, P.M. 1958b. Studies of Reproduction and Feeding of Atlantic Cod (*Gadus callarias* L.) in the Southwestern Gulf of St. Lawrence. Journal Fisheries Research Board of Canada 15(6):1383-1402. |
| | | | | |
| FO 3NO; George's Bank, Gulf of Maine | Atlantic cod | Yellowtail Flounder | Pleuronectidae comprise from approximately 3% of cod diet by mass (Kohler and Fitzgerald 1969), 6-32% of cod diet by volume (Powles 1958b), and up to 40% composition (Waiwood and Majowski 1984) in the Gulf of St. Lawrence. | Powles, P.M. 1958b. Studies of Reproduction and Feeding of Atlantic Cod (*Gadus callarias* L.) in the Southwestern Gulf of St. Lawrence. Journal Fisheries Research Board of Canada 15(6):1383-1402. |
| | | | | Kohler, A.C., and Fitzgerald, D.N. 1969. Comparisons of Food of Cod and Haddock in the Gulf of St. Lawrence and on the Nova Scotia Banks. Journal Fisheries Research Board of Canada 26(5): 1273-1287. |
| | | | | Waiwood, K. and Majkowski, J. 1984. Food consumption and diet composition of cod, *Gadus morhua*, inhabiting the southwestern Gulf of St. Lawrence. Environmental Biology of Fishes Vol II 1:63-78. |
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| FO 5YZ (Gulf of Maine and George's Bank) | Atlantic Halibut | American Plaice | American Plaice less than 35cm make up to 13.6% of cod diet on the Newfoundland-Labrador Shelf (Bundy *et al.* 2000). | Bundy, A., Lilly, G.R., and Shelton, P.A. 2000. A mass balance model of the Newfoundland-Labrador Shelf. Can. Tech. Rep. Fish. Aquat. Sci. 2310:1-157. |
| | | | | |
| FO 5Z (George's Bank) | Atlantic Halibut | Winter Flounder | Flounder has been reported as a main fish prey item of Atlantic halibut through stomach content analyses (Nickerson 1978). They make up from 4% ("flatfishes"; Kohler 1967) to 13.6% ("flounders" including witch flounder; Bundy *et al*. 2000) of halibut diet (also see Cargnelli et al. 1999). | Bundy, A., Lilly, G.R., and Shelton, P.A. 2000. A mass balance model of the Newfoundland-Labrador Shelf. Can. Tech. Rep. Fish. Aquat. Sci. 2310:1-157.<br>Kohler, A.C. 1967. Size at Maturity, Spawning Season, and Food of Atlantic Halibut. Journal Fisheries Research Board of Canada 24(1): 53-66.<br>Nickerson, J.T.R. 1978. The Atlantic halibut and its utilization. Marine Fisheries Review 40(7): 21-25<br>Cargnelli, L.M., Griesbach, S.J., and Morse, W.W. 1999. Essential Fish Habitat Source Document: Atlantic Halibut, *Hippoglossus hippoglossus*, Life History and Habitat Characteristics. NOAA Technical Memorandum NMFS-NE-125: 1-17. |
| | | | | |
| FO 5Y (Gulf of Maine) | Atlantic Halibut | Witch Flounder | Flounder has been reported as a main fish prey item of Atlantic halibut through stomach content analyses (Nickerson 1978). They make up from 4% ("flatfishes"; Kohler 1967) to 13.6% ("flounders" including witch | Bundy, A., Lilly, G.R., and Shelton, P.A. 2000. A mass balance model of the Newfoundland-Labrador Shelf. Can. Tech. Rep. Fish. Aquat. Sci. 2310:1-157.<br>Kohler, A.C. 1967. Size at Maturity, Spawning Season, and Food of Atlantic Halibut. Journal Fisheries Research Board |

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| | | | flounder; Bundy *et al*. 2000) of halibut diet (also see Cargnelli et al. 1999). | of Canada 24(1): 53-66.<br>Nickerson, J.T.R. 1978. The Atlantic halibut and its utilization. Marine Fisheries Review 40(7): 21-25<br>Cargnelli, L.M., Griesbach, S.J., and Morse, W.W. 1999. Essential Fish Habitat Source Document: Atlantic Halibut, *Hippoglossus hippoglossus*, Life History and Habitat Characteristics. NOAA Technical Memorandum NMFS-NE-125: 1-17. |
| | | | | |
| FO 3LNO | Greenland halibut | Redfish species | Redfish species of all sizes make up approximately 25% of Greenland halibut diet on the Newfoundland-Labrador Shelf (Bundy *et al.* 2000). | Bundy, A., Lilly, G.R., and Shelton, P.A. 2000. A mass balance model of the Newfoundland-Labrador Shelf. Can. Tech. Rep. Fish. Aquat. Sci. 2310:1-157. |
| | | | | |
| Iceland | Haddock | Capelin | Capelin make up to 15% of haddock diet by weight in Iceland (Jaworski and Ragnarsson 2006). | Jaworski, A. and Ragnarsson, S.A. 2006. Feeding habits of demersal fish in Icelandic waters:<br>a multivariate approach. ICES Journal of Marine Science 63: 1682-1694. |
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| West Coast of Vancouver Island | Pacific cod | Pacific herring | Pacific herring occur in Pacific cod diets with 43% frequency on average, with peak occurrences of 75-100% at some times of the year off the West Cost of Vancouver Island (Ware and McFarlane 1986). | Ware, D.M. and McFarlane, J.A. 1986. Relative impact of Pacific hake, sablefish and Pacific cod on west coast of Vancouver Island herring stocks. International North Pacific Fisheries Commission Bulletin 47: 67-78. |
| | | | | |
| Prince Rupert District; Queen Charlotte Islands | Sablefish | Pacific herring | Pacific herring have been reported as the most important fish prey off the southwest coast of Vancouver Island, found in up to 20% of stomachs (Tanasichuk 1997), and comprise of 6% of diet by weight off Vancouver Island's west coast (Ware and McFarlane 1986). | Tanasichuk, R.W. 1997. Diet of sablefish, *Anoplopoma fimbria*, from the southwest coast of Vancouver Island. NOAA Technical Report NMFS 130: 93-97.<br>Ware, D.M. and McFarlane, J.A. 1986. Relative impact of Pacific hake, sablefish and Pacific cod on west coast of Vancouver Island herring stocks. International North Pacific Fisheries Commission Bulletin 47: 67-78. |

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