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$F_{35\%}$ Revisited Ten Years Later

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Abstract.—This paper reviews the original derivation of the $F_{35\%}$ (later $F_{40\%}$) harvest strategy, which consists of fishing at a rate that reduces spawning biomass per recruit to 35% (or 40%) of the unfished value, and investigates its applicability to long-lived stocks with low resiliency, such as some of the Pacific Coast rockfishes *Sebastes* spp. The life history parameters are unimportant (at least in deterministic calculations), but the possibility of extremely low levels of resiliency—well below the bounds of the original analysis—does render the strategy unworkable in the sense that there is no harvest rate that will obtain a large fraction of the maximum sustainable yield (MSY) across the entire range of possibilities. At low but still workable levels of resiliency, the $F_{40\%}$ strategy results in undesirably low levels of biomass and recruitment by present-day standards. That can be cured by adopting a higher target for spawning biomass per recruit, though at some cost in yield. A purely biomass-based strategy and a modified F_{MSY} strategy are discussed as alternatives for cases where adequate historical data are available.

Summary of the Original Derivation

The $F_{35\%}$ (later $F_{40\%}$) harvest strategy consists of fishing at a rate that reduces spawning biomass per recruit—equivalent to lifetime egg production—to 35% (or 40%) of the unfished value. Its development was motivated by the need of the North Pacific Fishery Management Council for a harvest rate to use in setting levels of acceptable biological catch for Alaska groundfish. At that time, the acceptable biological catch was defined in principle (with some qualifications) as the yield obtainable at F_{MSY}, which is the constant fishing mortality rate that results in the maximum sustainable yield (MSY). But only for Bering Sea walleye pollock *Theragra chalcogramma* was an estimate of F_{MSY} available. For the other stocks a variety of rules were used, including $F_{0.1}$ (the rate that reduces marginal yield per recruit to 10% of its unfished value), $F = M$ (fishing mortality was set equal to natural mortality), and even F_{MAX} (the rate that maximizes yield per recruit.) It was not at all clear how any of these harvest rules compared with fishing a given stock at F_{MSY}, although it seemed likely that F_{MAX} in particular would be a good deal more aggressive.

The approach in the original paper (Clark 1991) was based on an earlier assessment of widow rockfish *Sebastes entomelas* by Lenarz (1984), who plotted yield curves for a range of plausible spawner–recruit (S−R) relationships and picked a value of F that would provide something close to the MSY for all of them. What Clark (1991) did was to apply Lenarz' procedure to a wide range of groundfish life history parameters and S−R curves and to investigate the relationship between the optimum F located in each case and the life history parameters. It turned out that in deterministic calculations, the optimum F was always close to the level that reduced spawning biomass per recruit to 35% of the unfished value. Happily, it was also close to $F_{0.1}$ and M in cases where the recruitment and maturity schedules coincided.

A later paper (Clark 1993) extended the analysis to cases with random and serially correlated recruitment variation and concluded that $F_{40\%}$ would be a better choice overall than $F_{35\%}$. Mace (1994) also recommended $F_{40\%}$ on the basis of deterministic calculations.

The findings in the original paper depended on the range of cases chosen for consideration. The results were not at all sensitive to the life history parameters, but they were quite sensitive to the form of the S−R curves considered and the limits placed on the slope parameter. In Clark (1991) both Beverton–Holt and Ricker curves were considered, the latter because Bering Sea walleye pollock and some Atlantic cod *Gadus morhua* stocks appeared to have dome-shaped S−R relationships. The slope parameter was discussed in terms of the density-dependent multiple by which spawner productivity at very low stock sizes would exceed spawner productivity at the unfished stock level. If we call this multiple D, then

$$(R/S)_{S=0} = D(R/S)_{\text{UNFISHED}} = D(R_0/S_0),$$

where R_0 and S_0 denote the unfished levels of re-

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cruitment and spawning biomass. At the outset, D values of 2, 4, 8, 16, and 32 were considered. The low end was excluded on the grounds that it implied a maximum sustainable F lower than M and the high end because it implied no significant reduction in recruitment even at $F = 1.0$. The analysis was then performed with the values 4, 8, and 16.

The method of choosing a range of values for the S−R slope parameter in Clark (1991) was admittedly brief and sketchy, but in fact it agreed very well with the results of a wide-ranging review of empirical S−R data by Mace and Sissenwine (1993) that was used by Mace (1994) to recommend that values of D (the reciprocal of her τ) between 3 and 20 be considered as a realistic range.

Behavior of Less Resilient Stocks

The Pacific Fishery Management Council, which manages the groundfish fisheries off the coasts of Washington, Oregon, and California, is concerned about recent declines and the apparently low productivity of some stocks (particularly those of rockfish *Sebastes* spp.) that have been exploited at the $F_{35\%}$ rate or, more recently, the $F_{40\%}$ rate. It is reasonable to ask whether the original analysis can be safely applied to long-lived Pacific stocks that may not be as resilient as the heavily fished Atlantic stocks that Clark (1991) and Mace (1994) mainly relied on when doing their analyses.

To answer that question, Figure 1 shows calculations of the sort presented in Clark (1991), with these differences:

(1) The life history parameters are those of Pacific ocean perch *Sebastes alutus* (often called POP; Ianelli and Zimmerman 1998), which has a lower rate of natural mortality ($M = 0.05$) and a later age of 50% recruitment and maturity (10 years) than any of the cases considered in Clark (1991).

(2) Consistent with all POP assessments known to the author, only Beverton–Holt S−R relationships are considered. None of the spawner−recruit data sets for Pacific Coast rockfish stocks shows a dome-shaped relationship (Dorn 2002, this issue).

(3) Lower levels of resiliency (values of D) are considered, that is, values of 1.5, 2, and 3 are considered along with 4, 8, and 16.

The life history parameters have virtually no effect. All of the graphs in Figure 1 look almost the same as the corresponding graphs in Clark (1991) referring to the standard groundfish life history, where $M = 0.2$ and 50% recruitment and maturity occur at age 5. The only difference between the two sets of graphs is that all the values of F are much higher for the standard groundfish.

The exclusion of Ricker curves increases the optimum level of spawning biomass per recruit (spr). Considering only the curves corresponding to $D = 4$, 8, and 16 (as in the original paper), the optimum occurs at 43% rather than near 35% (Figure 1D).

Allowing values of D lower than 3 or 4 changes part of the picture substantially. Down to $D = 3$, it is possible to locate a value of spr and the corresponding F (approximately $F_{45\%}$) that obtains the bulk of the MSY for all of the candidate S−R curves. Allowing even lower minimum values of D rapidly reduces the ''optimum'' value of F to $F_{60\%}$ and $F_{70\%}$, which would obtain not much more than half of the MSY for most of the candidate curves (Figure 1D).

On the other hand, the lower values of D do not upset the very robust relationship between relative biomass and relative yield (Figure 1C) reported in the earlier paper. In principle, therefore, a biomass-based strategy designed to maintain stock biomass in the vicinity of 40% of the unfished level should work well even for stocks with very low resiliency.

Developments during the 1990s

When the $F_{40\%}$ strategy was developed, the main concern was obtaining a large fraction of the MSY in the long term. Biomass levels were not considered important in themselves, especially in Alaska, where it was clear that environmental changes were causing large changes in the abundance of many stocks that were hardly exploited. During the 1990s, however, the exercise of defining overfishing and the requirements of recent federal legislation have made biomass levels important in themselves. There is now a requirement to consider how current biomass compares with unfished biomass, B_0, or the MSY biomass, B_{MSY}.

The biomass levels corresponding to $F_{35\%}$ were not even reported in the original paper (Clark 1991). At $F_{40\%}$, the deterministic equilibrium biomass for the POP example is 20–35% of B_0 for $D \geq 4$, but it drops fast at lower levels of D (Figure 1E). Some people have stated that any stock below 25% of the unfished abundance is overfished (e.g., Parker et al. 2000). By this standard, even with $D \geq 4$, any group of stocks fished at $F_{40\%}$ would be sure to include some that would qualify as overfished as a result of normal recruitment variation.

Another measure of overfishing is reduced re-

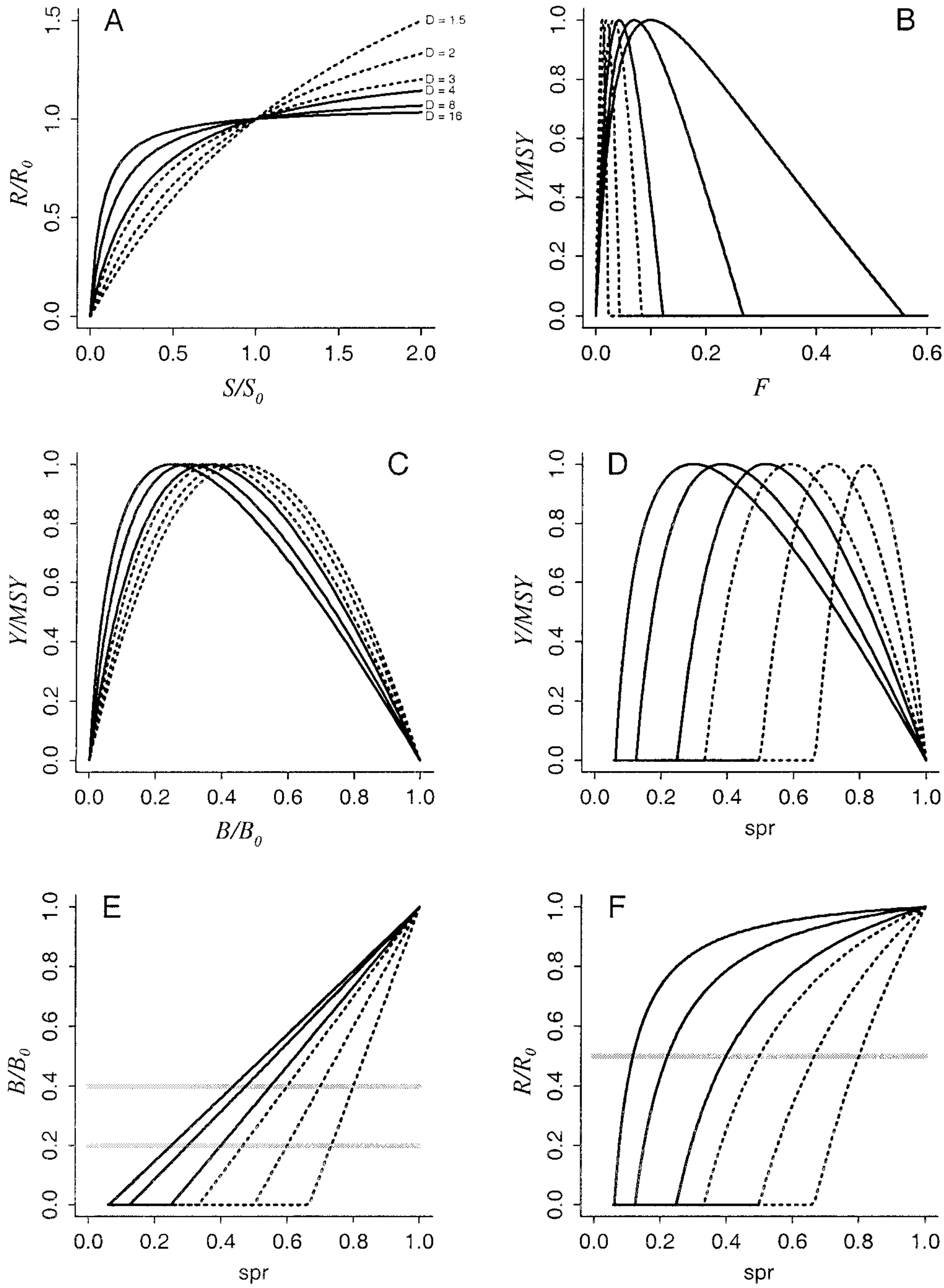

FIGURE 1.—Equilibrium yield, biomass, and recruitment for a range of spawner−recruit (S−R) curves for Pacific ocean perch (shown in panel **A**), where S_0 and R_0 represent the unfished levels of spawning biomass and recruitment, respectively. The solid lines represent the S−R curves considered in Clark (1991), the dashed lines less productive ones. The parameter D is spawner productivity (R/S) at $S = 0$, expressed as a multiple of the unfished value. Panels **B, C,** and **D** show the yield (Y) relative to the maximum sustainable yield (MSY) as a function of instantaneous fishing mortality (F), spawning biomass (B) relative to its unfished value (B_0), and spawning biomass per recruit relative to the unfished value (spr). Panels **E** and **F** show the equilibrium spawning biomass and recruitment (relative to their unfished values) as functions of relative spawning biomass per recruit.

cruitment, a common standard being a fishing mortality rate that reduces expected recruitment to less than one-half of the unfished or maximum level (Myers et al. 1994). For $D = 4$, $F_{40\%}$ reduces recruitment by about half, and for lower values of D it reduces recruitment even more (Figure 1F). So by this standard, too, the $F_{40\%}$ strategy borders on overfishing, and for less productive stocks, it actually crosses the line.

Alternative Target Levels of Spawning Biomass per Recruit

While in some respects $F_{40\%}$ may now appear to be too high, a harvest rate based on a different target (e.g., $F_{50\%}$), may still be attractive. Any harvest rate of this sort has the advantages of accounting for differences in life history parameters and finessing uncertainty about the exact form of the S−R relationship. The challenge is simply to choose a target that achieves a good balance regarding average yield on the one hand and average abundance on the other. The objectives may have changed, but the basic approach may still be useful.

The paramount question in attempting to choose a different target is, as before, what kind of S−R relationships and especially how low a value of D to consider. A fairly conservative approach for POP would be to limit the analysis to Beverton–Holt curves and to require that the strategy perform tolerably, in terms of both yield and abundance, for values of D down to, say, 3. As explained above, there is no good general-purpose, spr-based harvest rate if values of D below 3 must be allowed for. (A referee commented that while the Beverton–Holt curve may be conservative for the purpose of simulating harvest strategies, it is not necessarily conservative for the purpose of estimating the slope of a spawner−recruit curve at the origin. A Ricker curve may give a lower estimate in a particular case, and Myers et al. [1999] show that the Ricker equation on a logarithmic scale should generally give a more reliable estimate than other formulations. It would be quite sensible in practical work to estimate the slope at the origin using a Ricker curve [or some other method] and then use a Beverton–Holt curve with that slope estimate for simulating harvest strategies.)

As emphasized by Mace (1994), the first requirement of a target harvest rate is that it be sustainable. This is not an issue for any rational target when $D \geq 4$, but $F_{40\%}$ is just barely sustainable for $D = 3$, while $F_{60\%}$ is sustainable down to $D = 1.5$ (Figure 2A).

The harvest rate should maintain biomass and recruitment at some ‘‘healthy’’ level, however defined. The MSY biomass level is 25–40% of the unfished biomass, and the corresponding recruitment is 60–80% of the unfished level (Figure 2B). The middle of these ranges may look pretty low to some, especially when regarded as averages from which stocks will make excursions to lower levels.

One could choose 40% of the unfished biomass as a target on the grounds that it is an upper limit for B_{MSY} and, as mentioned above, it is the target biomass for a biomass-based strategy. The equilibrium biomass at $F_{40\%}$ (labeled $B_{40\%}$ in Figure 2D) is always less than 40% of the unfished value, and it is near zero for $D = 3$ (Figure 2D). Meanwhile, $B_{50\%}$ (at $F_{50\%}$) is near the 40% target for most values of D but drops steeply below $D = 4$, and $B_{60\%}$ is near 50% of the unfished value for most of the range but stays above 40% even at $D = 3$. The results of $F_{40\%}$, $F_{50\%}$, and $F_{60\%}$ are similar when the measure is relative recruitment (Figure 2E) or biomass relative to B_{MSY} (Figure 2F). For the purposes of assuring sustainability and maintaining healthy biomass levels even for unproductive stocks, therefore, something like $F_{50\%}$ or $F_{60\%}$ would be required.

The drawback of a higher target spr is forgone yield from stocks that are in fact of average or better productivity, amounting to about 10–15% of the MSY for $F_{50\%}$ and 20–30% of the MSY for $F_{60\%}$ (Figure 2C).

In summary, a harvest rate based on a target spr higher than 40% may serve present-day objectives reasonably well. Choosing such a rate requires deciding how low a value of D to allow for, how high a level of biomass to aim for, and implicitly how much of a yield penalty is tolerable. It also requires a proper treatment of the nature and consequences of recruitment variability.

Alternative Harvest Strategies

The most robust strategy reported in the original paper (Clark 1991) was a purely biomass-based strategy that consists of nothing more than maintaining spawning biomass at around 40% of the unfished level (Figure 1C). This strategy avoids uncertainty about the form and resiliency of the S−R relationship altogether, and it works even for extremely unproductive stocks. It also avoids the poor outcomes that can result from a poor estimate of the natural mortality rate when a harvest rate based on spr is calculated.

There are two difficulties with this strategy. The

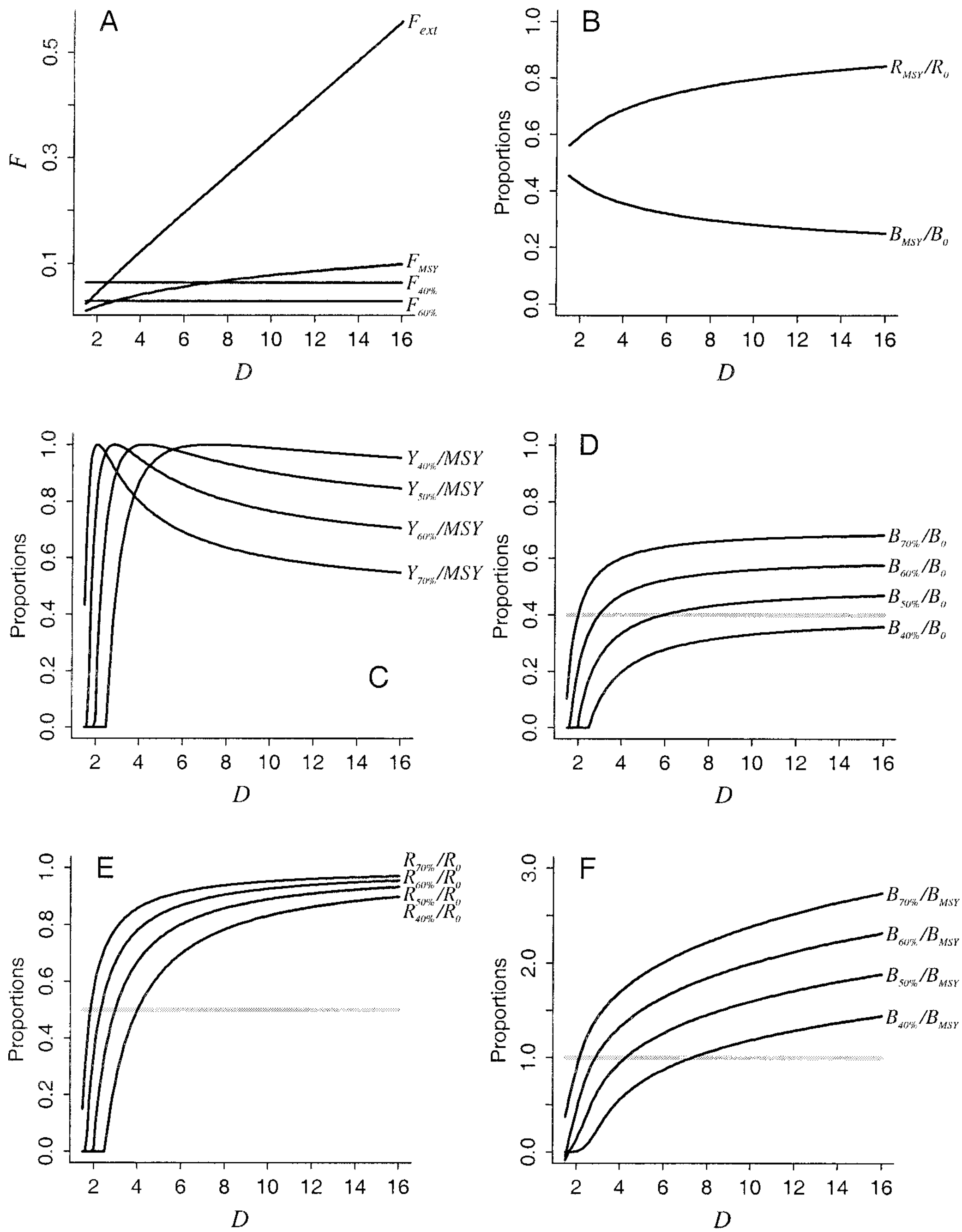

FIGURE 2.—Various features of the Pacific ocean perch stock as functions of the resiliency parameter D, including **(A)** instantaneous fishing mortality (F_{ext} is the maximum sustainable fishing rate), **(B)** recruitment and biomass at the MSY level relative to their unfished levels, **(C)** yield (relative to MSY) at various fishing mortality rates ($Y_{40\%}$ is the yield at $F_{40\%}$, and so forth), **(D)** and **(E)** biomass and recruitment relative to their unfished levels, and **(F)** biomass relative to the MSY level.

first is that unfished biomass can be difficult to determine. It is now clear that the abundance and productivity of many North Pacific stocks change with oceanic regime shifts (Francis et al. 1998), so that historical data may not be a reliable indicator of what unfished abundance would be at present. A subtle problem peculiar to stocks with low resiliency is that the unfished ''equilibrium'' occurs at a point where the S−R curve is still quite sloped (Figure 1A), so excursions from the equilibrium point are only weakly damped, even in the absence of fishing. In this case one would expect considerable variation in unfished abundance, so that an estimate from any given point in time could be well above or below the long-term average even in the absence of climate changes.

The second difficulty is that even with some kind of smoothing mechanism, quota recommendations under a purely biomass-based policy will be quite sensitive to changes in estimates of unfished and present biomass. A harvest rate strategy is also sensitive to changes in biomass estimates (which may be due either to real changes in the stock or, more often, to changes in stock assessment data or methods), but a biomass-based strategy would likely be much more so.

Another alternative harvest strategy is to use the available historical stock and recruitment data to estimate F_{MSY} and then fish at some fraction thereof. Ten years ago, almost all of the catch-at-age data series were too short for that, but by now fairly long series are available for a number of the major target species. For Alaska stocks, the data generally lack any information about recruitment at low biomass levels, but that may be less of a problem for stocks in Washington, Oregon, and California. An attraction of the F_{MSY} approach is that it is less sensitive to errors in the estimate of natural mortality than a harvest rate derived from a target spr when both the present biomass estimate and the F_{MSY} estimate are based on the same age-structured assessment, as they usually are (Clark 1999). The key issue is whether the S−R data are adequate, particularly at low biomass levels.

An intermediate strategy in the case where only a few S−R data were available would be to use those points to set a range on the likely value of D and then to choose a target spr and F accordingly.

Conclusion

The $F_{40\%}$ strategy was developed to obtain a large fraction of the MSY in cases where the available data did not allow an estimate of either F_{MSY} or unfished biomass, which is still the case for many stocks. The original paper did not consider biomass levels at all, although a later paper (Clark 1993) reported that biomass levels below 20% of the unfished level would not be uncommon in stocks with strong serial correlation in recruitment that were fished at $F_{40\%}$.

In the 10 years since the original analysis was published, maintaining biomass levels and limiting fishing mortality to levels below F_{MSY} have become important management objectives (along with obtaining a high yield). Clearly, an $F_{40\%}$ harvest rate will not accomplish these objectives for stocks where $F_{MSY} < F_{40\%}$, which corresponds roughly to $D < 8$. For those cases, a higher target level of spr or a different harvest strategy is required.

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