WILLAPA BAY POLICY DEVELOPMENT: COMPARISION AMONG POLICY ALTERNATIVES – MODEL DESCRIPTION AND RESULTS

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Introduction:

In January 2022, the Fish Committee assigned WDFW staff (Staff) the task to analytically compare the three Willapa Bay Policy Alternatives (Alt 1, Alt 2, and Alt 3). To achieve this comparison, Staff initially designed a model that included estimates of parameter uncertainty (e.g., means and variation around the means (standard deviations) of parameters such as the number of adults returning to Willapa Bay per smolts released, SARs). This model was first presented at a special Fish Committee meeting on May 13, 2022, and then in more detail at a special Fish Committee meeting on June 10, 2022. Although the model directly compared the three policy alternatives, it was clear to Staff that using a model that included uncertainty was overly complicated and was not useful for the intended purpose of the analysis. Following the June 10, 2022, Fish Committee meeting, Staff retooled the model by reducing the number of parameters and eliminating uncertainty (e.g., model used only means and not standard deviations). We refer to this model as Model 2. Staff provided a preview of Model 2 at the June 23, 2022, Fish Committee meeting, and a full presentation at the August 4, 2022, Fish Committee meeting. Due to time constraints, Staff was unable to complete the presentation on August 4.

This document provides a description of Model 2, a brief discussion of the sources of the parameter values used in the model, and a series of figures describing the results of the model. This is followed by a conclusion and a summary. We also discuss the limitations of the model.

Model Description

This model describes a simple version of nature and is intended to show how three primary multistate parameters interact with each other to produce specific outcomes associated harvest and the state of the wild (natural-origin) population. The three primary parameters are: (1) the number of smolts produced from a hatchery, (2) total run exploitation rate – the proportion of the total (hatchery- and natural-origin fish) run that is harvested, and (3) natural-spawning capacity – the carrying capacity of the natural environment with respect to the total number of spawners.

Number of smolts produced from a hatchery:

This parameter is one of the management goals for each of the policy alternatives and is a parameter that is controlled by WDFW (as opposed to controlled by nature; see natural-spawning capacity, below). The model was run iteratively using 23 different smolt production values: 1,000,000 smolts produced to 12,000,000 smolts produced in 500,000 smolt intervals. For example, in the first iteration of smolt production we used a value of 1,000,000 smolts produced, and in the second iteration we used 1,500,000 smolts produced. In the twenty-third iteration we used 12,000,000 smolts produced.

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Total run exploitation rate
A form of this parameter is also a management goal for each policy alternative, and as with smolt production this parameter is controlled by WDFW. The model was run iteratively using 16 different exploitation rate values: 30% of the total run is harvested up to 60% of the total run is harvested in 2% intervals. For example, in the first iteration of exploitation rates we used a value of 30%, and in the second iteration we used 32%. In the sixteenth iteration we used 60%.

Natural-spawning capacity
This parameter defines the spawning capacity of the natural environment and is used as part of the Ricker equation (see "D" below and in Figure 1). This parameter is controlled by nature, and we selected three capacity values based on assumed low, moderate, and high capacity for fall Chinook spawning in an idealized Willapa Bay river. These values are 2000, 4000, and 6000 fish.

Model runs
The model was run for 15 generations, with the first generation starting with 100% wild or natural-origin fish that spawned naturally at the capacity value for that iteration. Each model run consisted of one of the 23 smolt production scenarios, one of the 16 exploitation rates, and one of the three capacity values. There are 23*[2]16*3 = 1104 combinations of these three parameters. Therefore, the model was run 1104 * 15 generations = 16,560 cycles.

Schematically, the model consists of fish originating in two different environments (hatchery and natural) and takes the hatchery- and natural-origin populations through complete life cycles – from spawning adults to returning adults that are either harvested or escaped harvest and spawn (in either the hatchery or natural environment) or are removed as surplus hatchery-origin fish (Figures 1 and 2).

The following describes each of the states (boxes) and the transition between states (arrows) in the model. See Figure 1, which portrays one generation.

A. Red dashed box A is the Hatchery Environment which consists of hatchery-origin broodstock (HOB) and natural-origin broodstock (NOB). The total number of hatchery spawners (HOB + NOB) is fixed for each smolt production parameter value by assuming a fecundity value = 3430 eggs per female[3] and a 1:1 sex ratio. In other words, the total number hatchery spawners is smolt production value divided by 3430 times 2 (2=male and female broodstock). For example: 1,000,000/3430*2 = 583 hatchery spawners. In all generations except generation 1, hatchery broodstock consists of a combination of hatchery-origin adults and natural-origin adults. From generation 2 through 15 NOB is fixed at 20% of the natural-origin escapement (see J below). In generation 1, the first year of the program, hatchery broodstock is 100% natural-origin since hatchery-origin fish are first generated by hatchery spawning in generation 1. Although the total number of hatchery spawners is fixed, HOB and NOB will vary based on the number of natural-origin fish that escape harvest.
B. Red dashed box B is the Natural Environment which consists of hatchery-origin spawners (HOS) and natural-origin spawner (NOS). In generation 1 all natural spawners were of natural-origin and the number of natural spawners equaled the capacity value for that iteration (i.e., 2000, 4000, or 6000). In generations 2 through 15 natural spawners are composed of both HOS and NOS, which are determined by the remaining steps in Figure 1. See also Figure 2.
C. Number of smolts produced from a hatchery, as discussed above

[2] When in an equation the symbol * indicates multiplication
[3] Mean fecundity value for fall Chinook in Willapa Bay hatcheries

D. We converted the total number of natural spawners to natural-origin recruits using the Ricker equation[4], with the alpha = 3 and spawning capacity equal to either 2000, 4000, or 6000. See G below.
E. We used relative fitness as method to consider the consequences of mixing hatchery- and natural-origin fish in both the hatchery and natural environments. Relative fitness occurs in both the upper and lower portion of Figure 1 and it concerns the average fitness of the population spawning in the hatchery environment (HOB + NOB) and the average fitness of the population spawning in the natural environment (NOS + HOS), respectively (Figure 2). We used the recursive equations from Ford (2002)[5], which requires values for eight parameters. We used two different selection regimes. Throughout the model runs, in the moderate selection regime relative fitness values ranged from 0.60 – 1.00, and 0.54 – 1.00 for the natural- and hatchery-origin populations, respectively. In the weak selection regime relative fitness values ranged from 0.94 – 1.00 for both the natural- and hatchery-origin populations. The relative fitness values were used as a multiplier, as explained in F and G below.
F. The number of hatchery smolts produced was converted to the hatchery-origin run into Willapa Bay using the smolt to adult ratio (SAR) value = 0.00345[6]. Final hatchery-origin run values were calculated as smolts produced *SAR*relative fitness. For example, 1,000,000 smolts would produce 3450 adult returns if relative fitness was 1.00. If relative fitness was 0.54 or 0.94 adult returns would equal 1863 and 3243, respectively.
G. Natural-origin run into Willapa Bay was calculated as natural-origin recruits from the Ricker equation (D) times relative fitness. For example, if spawning capacity = 4000 and the number of natural spawners (HOS + NOS) equaled 7000, the Ricker equation would result in 3649 natural-origin recruits. If relative fitness equaled 0.65 or 0.95, the natural-origin run into Willapa Bay would be 2372 or 3468 fish.
H. Total run exploitation rate, as described above. The hatchery-origin run into Willapa Bay and the natural-origin run into Willapa Bay are both multiplied by the exploitation rate to produce the hatchery-origin and natural-origin harvest, respectively.
I. The portion of the hatchery-origin and natural-origin runs that are not harvested. This equals the hatchery-origin and natural-origin escapement, respectively. Escapement is calculated as Run – (Run * exploitation rate).
J. As discussed in A above, J is the proportion of the natural-origin run that is removed as natural-origin broodstock (NOB). See also Figure 2. In this model, this proportion is fixed at 0.20.
K. The proportion of the hatchery-origin escapement that returns to or is transported to the hatchery. This proportion is set at 0.572, which is the mean value for the proportion of the escapement that returned to Willapa Bay hatcheries 2010 – 2020.
L. As discussed in A above, the number of hatchery spawners is fixed by the smolt production parameter. Once NOB is determined (see J above) the number of hatchery-origin broodstock (HOB) is simply the number fixed by the smolt production parameter minus NOB.
M. The difference between the total number of fish that return to the hatchery (see K) and the number of fish needed for broodstock (HOB; see L) is the number of fish that were either pre-spawn mortalities or were surplus. These fish are removed from the model.
N. One minus the proportion of the hatchery-origin escapement that returns to or is transported to the hatchery (see K) is the number of fish that remain in the river. That is 1 – 0.572 = 0.428 is

[4] `R = alpha * S * exp(-beta * S)`, with R being number of recruits, alpha being the productivity parameter, S being the total number of natural spawners, and beta equal to 1 divided by spawning capacity.
[5] Ford, M.J. 2002. Selection in captivity during supportive breeding may reduce fitness in the wild. Conservation Biology 16 (3): 815-825.
[6] Average value for Forks Creek hatchery 2003-2016.

the proportion of the hatchery-origin escapement that remains in the river. A proportion of these fish encounter weirs currently in place in the Willapa, Naselle, and Nemah rivers. These fish are removed from the river. We used the 1 – the mean weir removal rate for fall Chinook in the Willapa River (2017 – 2020), which equals 1 – 0.263 = 0.737, as the proportion of the hatchery-origin fish that remain the river and spawn naturally.

O. Natural-origin escapement minus NOB (see J above) equals the natural-origin spawners (NOS)

Results

Figures 3 – 7 and 9 – 12, each containing four plots, provide model outcomes across the full range of smolt production (1 million to 12 million) and total run exploitation rates (0.30 to 0.60). We have grouped these results into sets. Some of the same plots are repeated in different sets to allow for direct comparisons within each set.

<u>Set 1: Figures 3 – 5</u> show the effects of smolt production and exploitation rates on (1) total harvest, (2) number of natural-origin spawners, (3) proportion of natural spawners that are of hatchery-origin (pHOS), and (4) relative fitness of the natural-origin population, for natural spawner capacity equal to 2000, 4000, and 6000 respectively. Across all three spawning capacity values as the number of smolts released from the hatchery increases total harvest increases (upper left plot). Harvest also increases as total exploitation rate increases; however, this effect is more pronounced at larger than at smaller smolt release sizes. For a given combination of smolt release size and exploitation rate (e.g., 5 million and 50%, respectively; see filled circles in Figures 3 – 5) as spawner capacity increases, total harvest also increases. This is due to a more productive natural environment as capacity increases – that is, as spawning capacity increases the number of natural-origin spawners increase (upper right plot), the fewer hatchery-origin natural spawners (pHOS is lower; lower left plot), and the more fit the natural-origin population (lower left plot).

As the number of smolts released from the hatchery increases the number of natural-origin spawners decreases, and the natural-spawning population changes from a population dominated by natural spawners (low pHOS) to a system dominated by hatchery-origin spawners (high pHOS). A population dominated by natural-origin spawners has a higher relative fitness, and therefore is more productive, than a population dominated by hatchery-origin spawners, with lower relative fitness and less productivity. An increase in the exploitation rate decreases the number of natural-origin spawners at smaller smolt releases, but at larger smolt releases the effect is less pronounced and depends on the natural spawner capacity.

<u>Set 2: Figures 6 and 7 (and 8)</u> show the effects of smolt production and exploitation rates on outcomes related to the natural environment or natural-origin populations, for moderate and weak selection, respectively. In Figures 6 and 7 the number of natural-origin spawners and relative fitness plots are repeated from Set 1. As the number of smolts released from the hatchery increases, the number of hatchery-origin natural spawners also increases. That is, the larger the hatchery production the greater the number of returning hatchery fish that stray to the natural environment and spawn naturally. This pattern is nearly opposite of the number of natural-origin natural spawners, and results in the increase in pHOS and decrease in relative fitness discussed in the Figures 3 – 5 set above. Increasing the exploitation rate will decrease the number of hatchery-origin spawners, but this effect is more pronounced at larger smolt releases than smaller releases.

The total natural-origin run is the product of the hatchery- and natural-origin fish spawning together in the natural environment. As the number of smolts released from the hatchery increases, the natural-origin run decreases, despite there being more total natural spawners. Part of this effect is due to the lower fitness of the hatchery-origin fish (compare Figure 6, with moderate selection, with Figure 7, with weak selection). However, the larger component of this effect is due to overloading the natural environment with hatchery-origin fish. This effect can be seen in Figure 8, where the natural-origin run, and the number of natural-origin spawners decline with an increase in the number of hatchery-origin spawners even in the absence of fitness differences between natural- and hatchery-origin natural spawners.

Figures 6 and 7 also show the pHOS = 0.5 contour. pHOS = 0.5 indicates equal number of hatchery- and natural-origin spawners, and results in a relative fitness ~0.844 for moderate selection and a relative fitness greater than 0.978 for weak selection. In this model, pHOS equal to or less than 0.5 is limited to smolt releases less than approximately 3 million (see also Figures 3 – 5), regardless of the exploitation rate and will result in the largest natural-origin runs.

<u>Set 3: Figures 9 and 10</u> show the effects of smolt production and exploitation rates on outcomes related to harvest, for moderate and weak selection, respectively. The harvest of hatchery-origin fish increases as smolt releases increase, and as expected, the largest increase in harvest occurs at higher exploitation rates. The harvest of natural-origin fish peaks at a moderate number of smolt releases and high exploitation rates and decreases from that point. The lowest natural-origin harvest occurs at the largest smolt releases regardless of exploitation rate. This is most-likely due to the lower productivity of the natural spawners when smolt release numbers are large. The total harvest mirrors the harvest of the hatchery-origin fish since the harvest of natural-origin fish is inconsequential compared with that of the hatchery-origin fish (compares scales for the two plots). Finally, the larger the number of smolt releases the more adult hatchery-origin fish are removed in the freshwater as surplus hatchery fish or at the weir as a minor control of pHOS. However, higher exploitation rates can reduce the number of “extra” hatchery fish produced by increasing their harvest. Selection strength in the natural environment has no impact on the harvest of hatchery-origin fish and only minor effects on the total harvest and the number of adult hatchery-origin fish removed in the freshwater.

<u>Set 4: Figures 11 and 12</u> show the effects of smolt production and exploitation rates on outcomes related to the run into Willapa Bay, for moderate and weak selection, respectively. The plots on the right side of the figures have been shown several times in the other sets. The hatchery-origin run increases as smolt releases increase because the hatchery-origin run is a value fixed by the smolt release size and a constant SAR (see Figure 1). Total exploitation rate has no effect on the size of the hatchery-origin run since harvest occurs after the size of the run is calculated. The total run reflects the hatchery-origin run because the natural-origin run is a minor component of the total run. Total harvest is a nearly straight conversion of the hatchery-origin run (i.e., hatchery-origin run times the exploitation rate), but is slightly distorted at the lower left-hand corner due to the relatively greater contribution to the total run from natural-origin fish at small smolt release sizes and low exploitation rates.

General conclusion

Considering the three primary parameters (number of smolt releases, total exploitation rates, and spawner capacity), increasing smolt production produced the greatest increase in the number of fish harvested and the greatest decrease to natural production, compared with comparable changes in exploitation rate and spawning capacity. These results are relatively independent of selection strength and relative fitness of the hatchery- and natural-origin fish that spawn naturally.

Model limitations

The model presented in this report (Model 2) is a heuristic and deterministic model that is intended to explore how the interaction of multistate parameters (smolt releases, exploitation rates, and spawning capacities) produce specific outcomes (e.g., total harvest). Since this model uses mean values for other parameters as constants (e.g., smolt to adult ratio or SAR = 0.00345) each time the model is run using the same set of multistate parameters values the model will produce exactly the same results. The model was parameterized using data from Willapa Bay fall Chinook populations, modeled as a system with one freshwater environment and one hatchery environment. The populations exist as single-year cohorts, with no overlapping age classes, and instantly go from smolts to returning adults, experiencing only constant environments and yearly climatic conditions. Therefore, the model cannot be used to calculate probabilities associated with any particular outcome or be used to forecast future conditions with any sense of certainty.

Summary

- As the number of smolts released from the hatchery increases, *total* harvest increases.
    - The harvest of hatchery-origin fish increases as smolt releases increase.
    - The harvest of natural-origin fish peaks at moderate number of smolt releases. The lowest natural-origin harvest occurs at the largest smolt releases regardless of exploitation rate.
    - Therefore, total harvest mirrors the harvest of the hatchery-origin fish since the harvest of natural-origin fish is inconsequential compared with that of the hatchery-origin fish.
- Total harvest also increases as total exploitation rate increases; however, this effect is more pronounced at larger than at smaller smolt release sizes.
- As the number of smolts released from the hatchery increases the number of natural-origin spawners decreases, and the natural-spawning population changes from a population dominated by natural spawners (low pHOS) to a system dominated by hatchery-origin spawners (high pHOS).
- A population dominated by natural-origin spawners has a higher relative fitness, and therefore is more productive, than a population dominated by hatchery-origin spawners, with lower relative fitness and less productivity
- As spawner capacity increases, the natural environment becomes more productive – that is, there is an increase in the number of natural-origin spawners, there are relatively fewer hatchery-origin natural spawners (pHOS is lower), and the natural-origin population is more fit.
- Increasing the exploitation rate will decrease the number of hatchery-origin spawners (HOS), but this effect is more pronounced at larger smolt releases than smaller releases.
- As the number of smolts released from the hatchery increases, the natural-origin run and the number of returning natural-origin spawners decreases despite there being a greater number of total natural spawners. This effect is mostly due to overloading the natural environment with hatchery-origin fish.
- With this model, maintaining a greater number of natural-origin spawners than hatchery origin spawners (pHOS less than or equal to 0.5) occurs when smolt releases are less than approximately 3 million, regardless of the exploitation rate. pHOS less than or equal to 0.5 will result in the largest natural-origin runs.

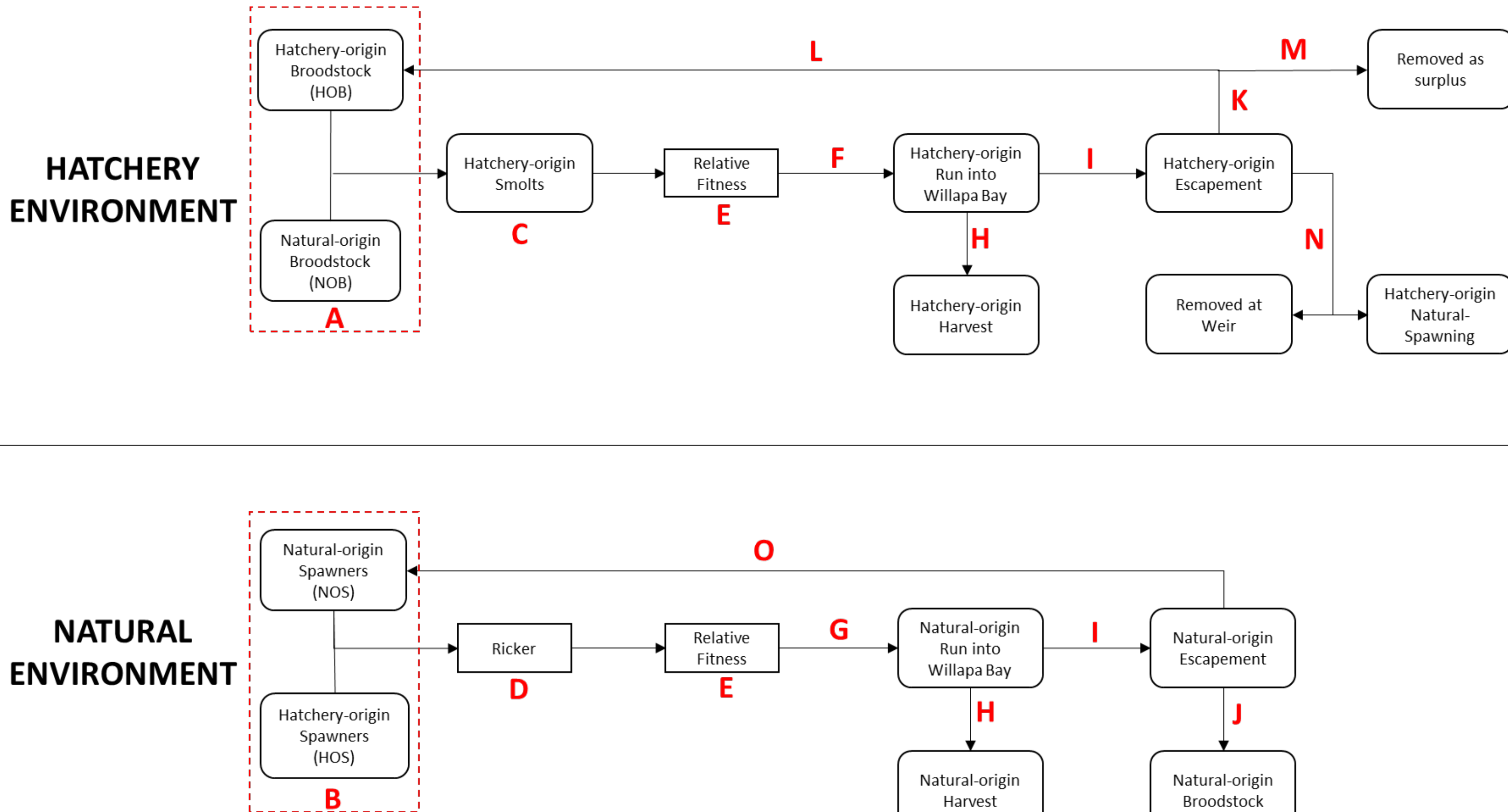

Figure 1. Schematic of the model. States (boxes) and transitions (arrows) with letters are described in the text. The titles Hatchery Environment and Natural Environment refer to the red dashed boxes in the upper and lower plots, respectively. These two environments are shown in more detail in Figure 2.

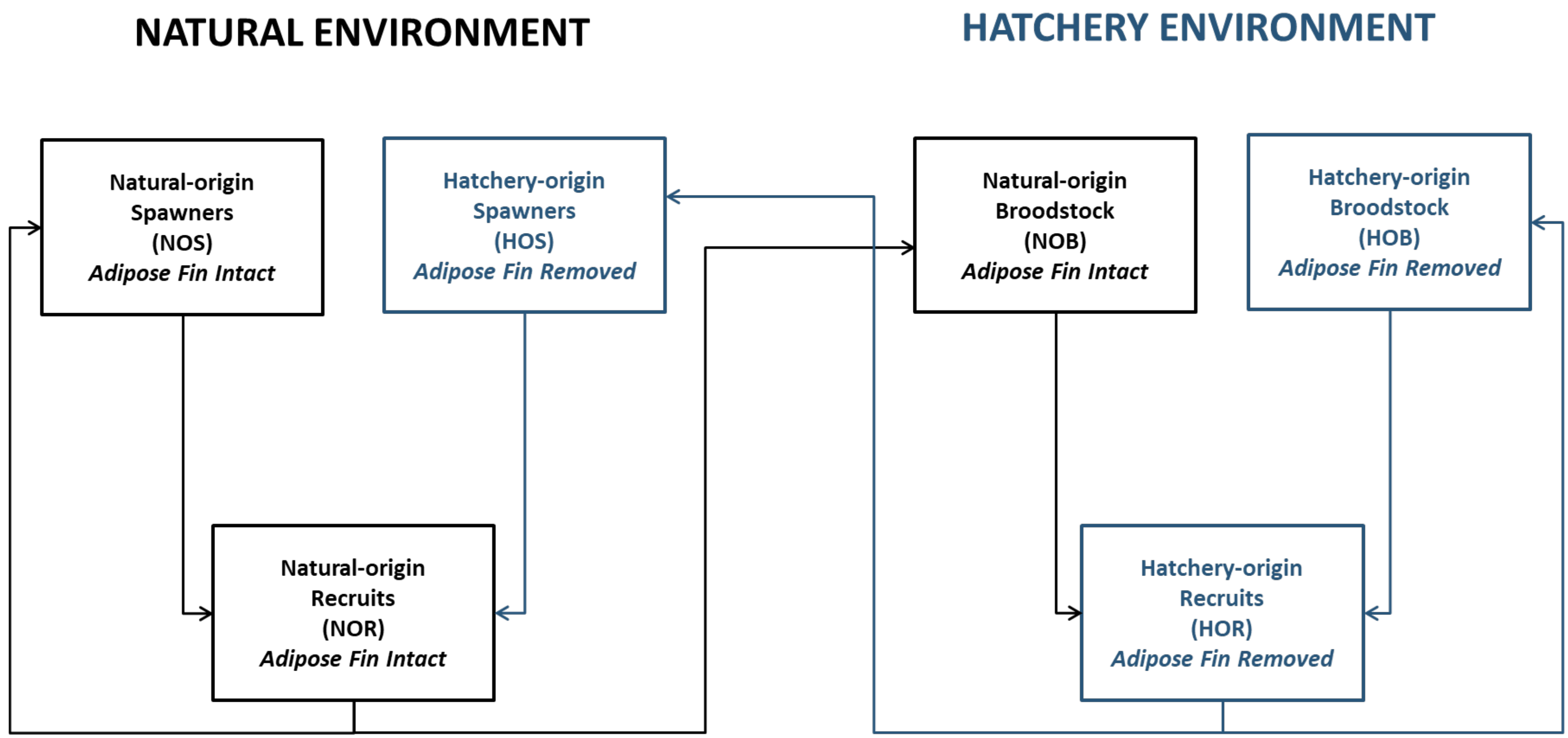

Figure 2. The interaction between the natural and hatchery environments. In the natural environment, natural- and hatchery-origin spawners spawn together to produce natural-origin recruits. In the hatchery environment, natural- and hatchery-origin broodstock spawn together to produce hatchery-origin recruits. Some of the natural- and hatchery-origin recruits are harvested. The remaining natural-origin recruits spawn either in the natural environment or in the hatchery as natural-origin broodstock. The remaining hatchery-origin recruits spawn in either the hatchery or in natural environment as hatchery-origin spawners. A portion of the hatchery-origin spawners are removed from the model (see Figure 1).

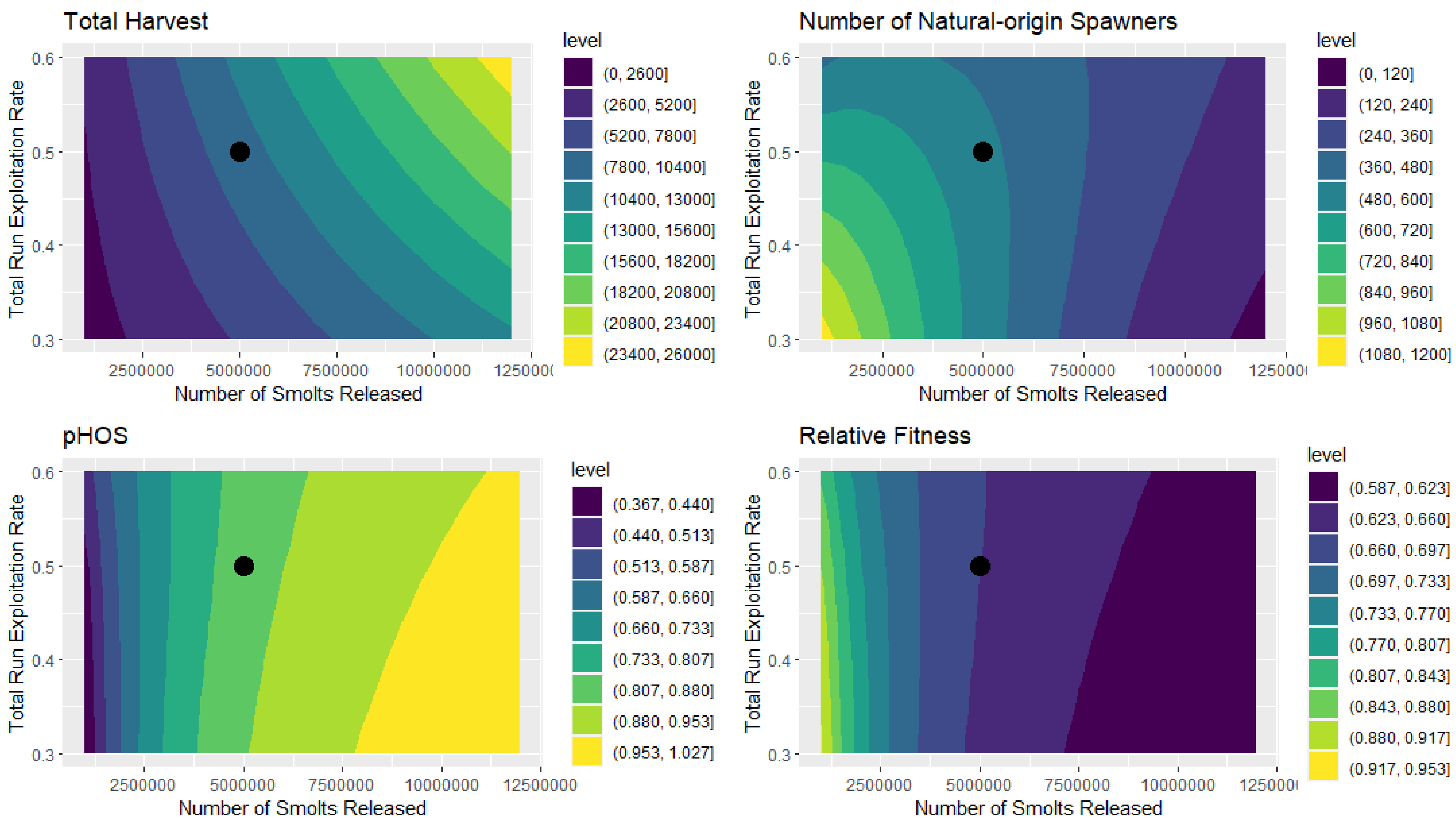

Figure 3. Contour plots showing the effects of different exploitations rates (y-axis) and smolt releases (x-axis) on Total Harvest (upper left), Number of Natural-origin Spawners (upper right), proportion of natural spawners that are of hatchery-origin (pHOS; lower left), and Relative Fitness of the natural-origin population (lower right). In all plots, Exploitation Rates range from 0.30 to 0.60 and the Number of Smolts range from 1 million to 12 million. Contours run from low values in dark purple to high values in yellow. Note that the scale for each plot is different. The black filled circle can be used as a point of orientation and is plotted at 5 million smolt releases and 0.50 exploitation rate. For these results natural-spawning capacity = 2000 and selection = moderate.

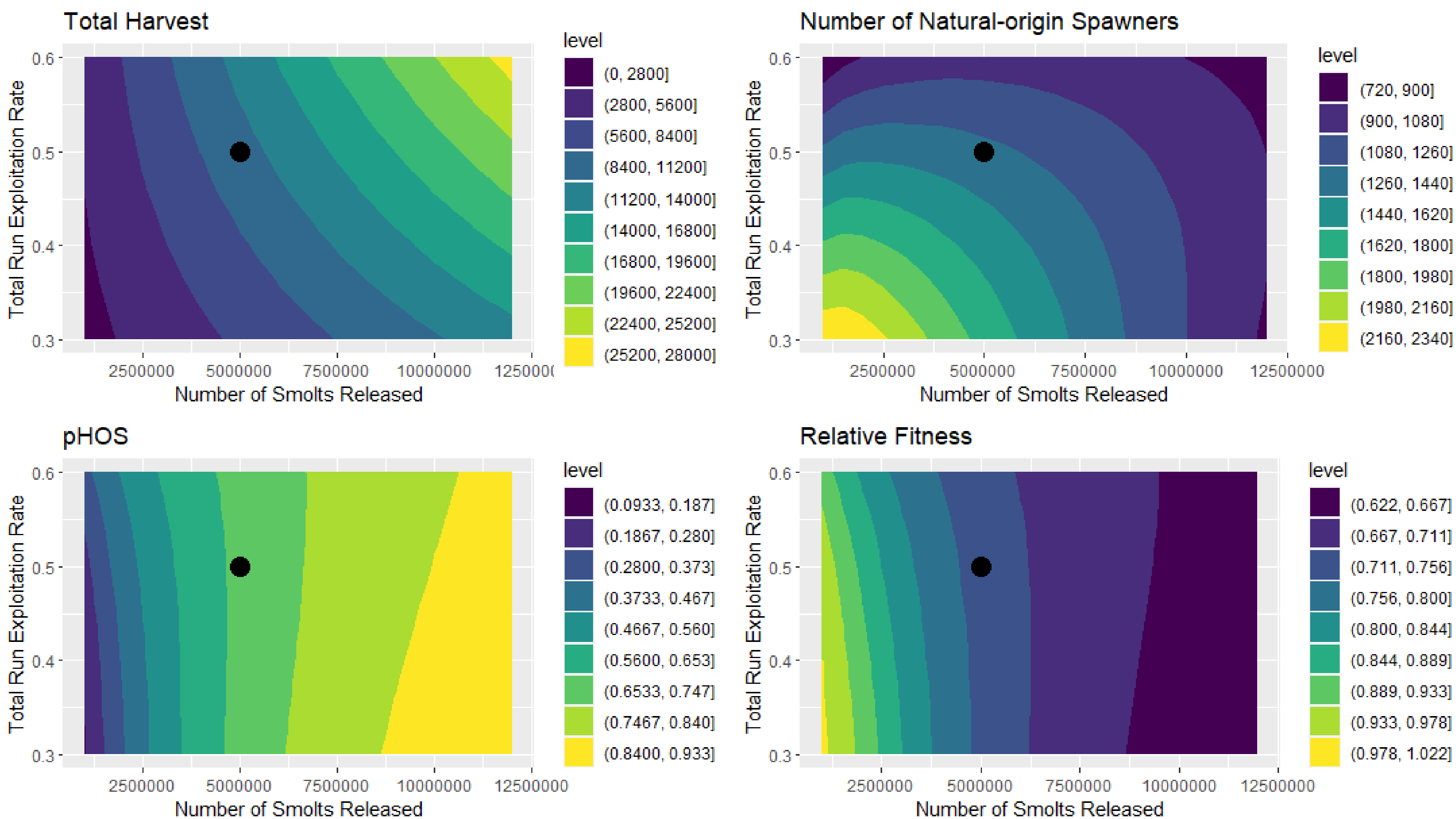

Figure 4. Same as Figure 3 except natural-spawning capacity = 4000

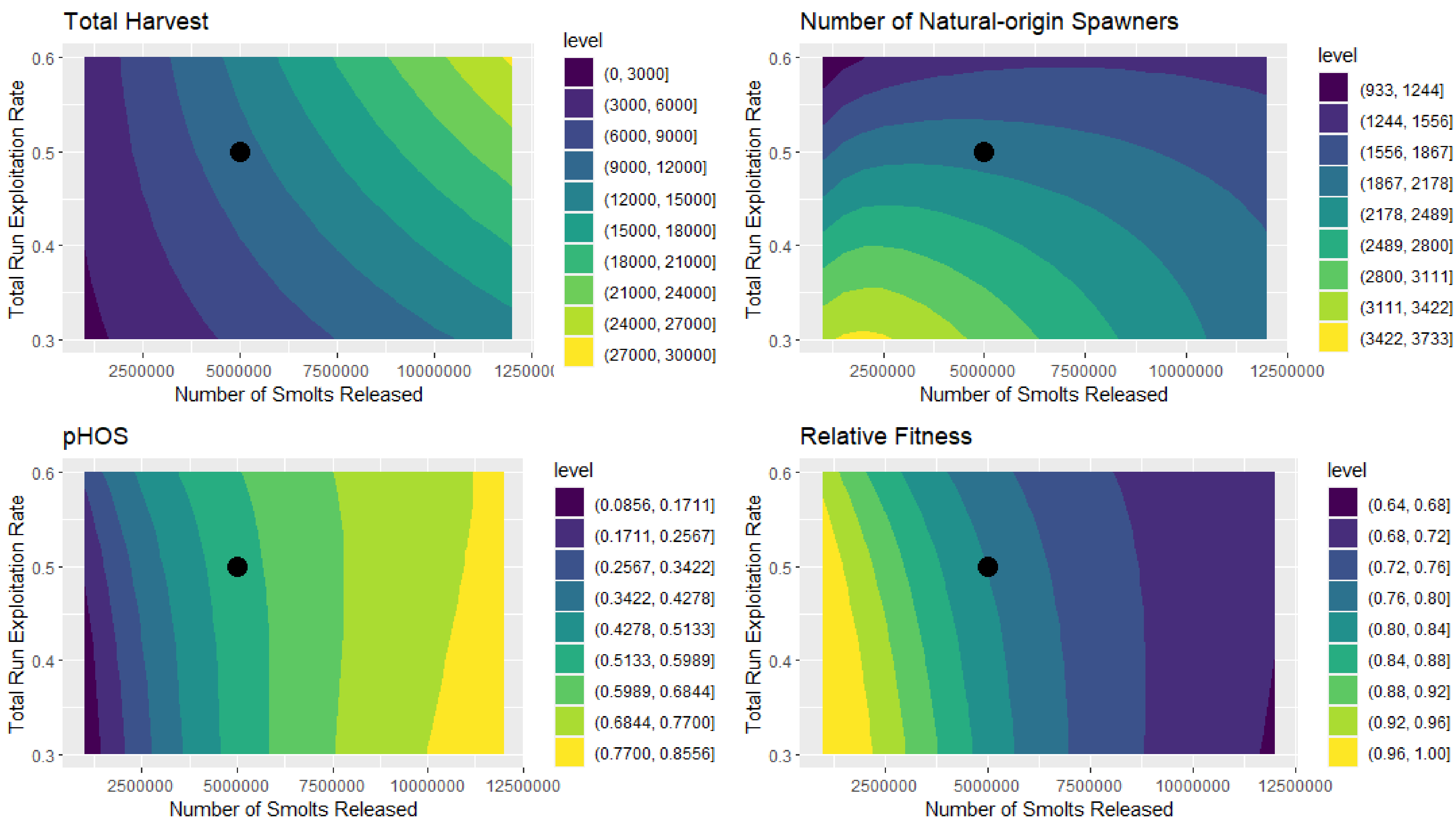

Figure 5. Same as Figure 3 except natural-spawning capacity = 6000

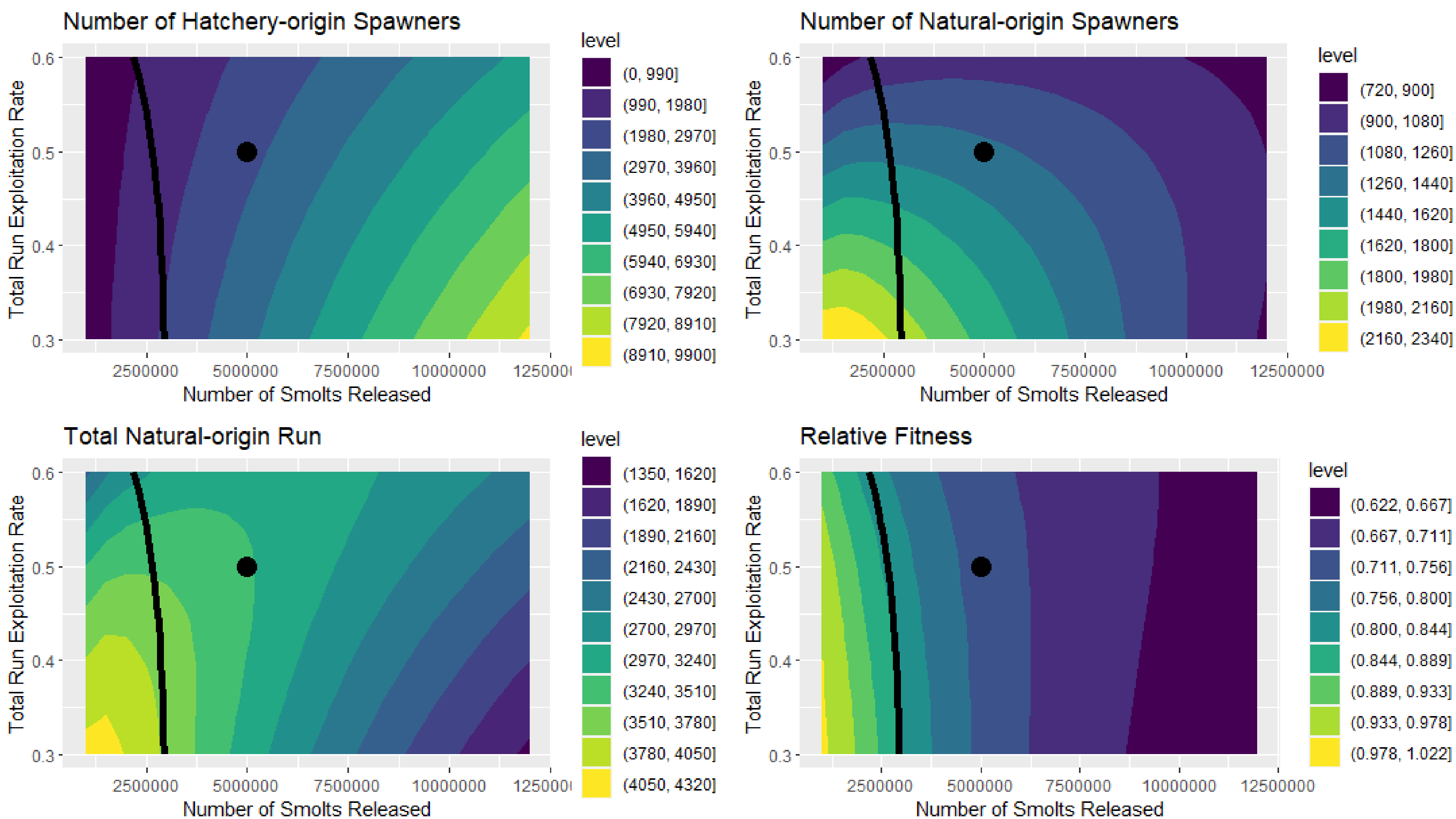

Figure 6. Same basic format as Figure 3 except here the contour plots show the effects of different exploitations rates (y-axis) and smolt releases (x-axis) on Number of Hatchery-origin Spawners (upper left), Number of Natural-origin Spawners (upper right; this repeats the upper right plot from Figure 3), Total Natural-origin Run (lower left), and Relative Fitness of the natural-origin population (lower right; this repeats the lower right plot from Figure 3). The heavy black line within each plot is an additional contour showing pHOS = 0.50. For these results natural-spawning capacity = 4000 and selection = moderate.

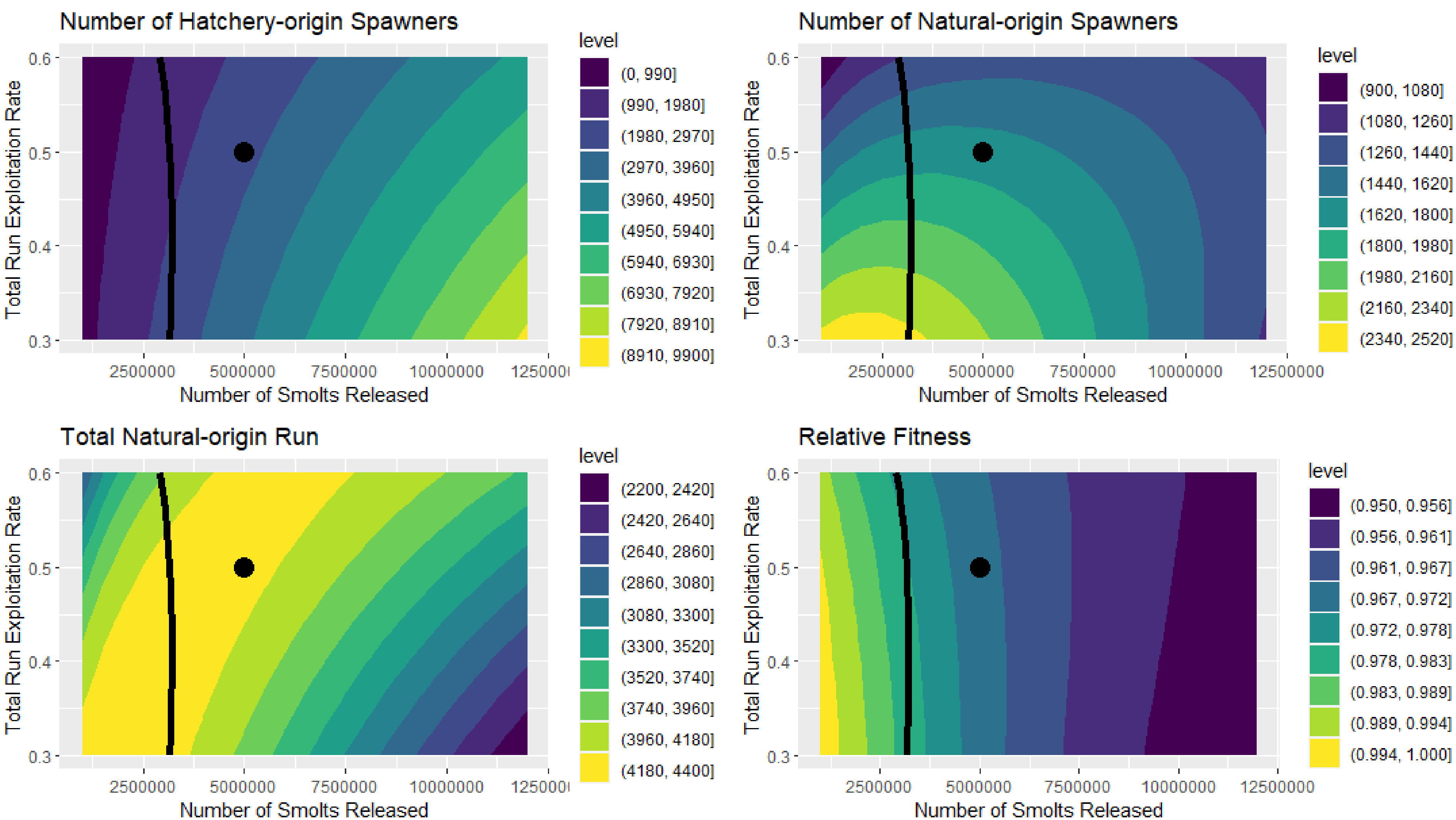

Figure 7. Same as Figure 6 except selection = weak.

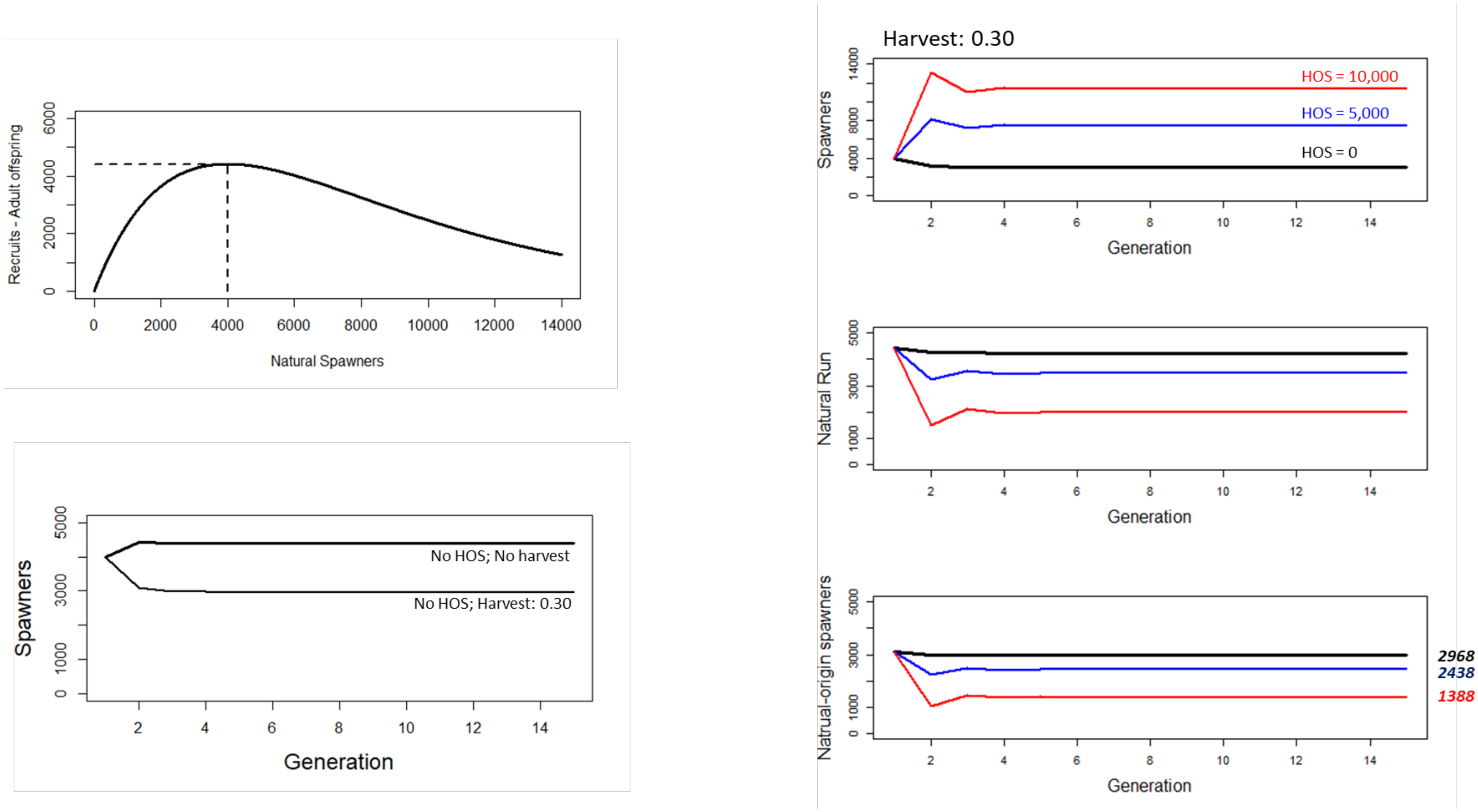

Figure 8. The effect of hatchery-origin spawners (HOS) on the number of total spawners, the size of the natural-origin run, and the number of returning natural-origin spawners, based on a Ricker spawner recruit curve (alpha = 3, spawner capacity = 4000; upper left plot), and no selection (i.e., no difference in the relative fitness of hatchery- and natural-origin fish spawning in the natural environment). With no HOS and no harvest of fish or an exploitation rate = 0.30 a population will stabilize at 4414 and 2968 individuals, respectively (lower left plot). Adding 5000 and 10,000 HOS to the natural spawning population results in an increase in the number of natural spawners (upper right plot), but a decline in the natural-origin run (middle right plot) and the number of returning natural-origin spawners (lower right plot).

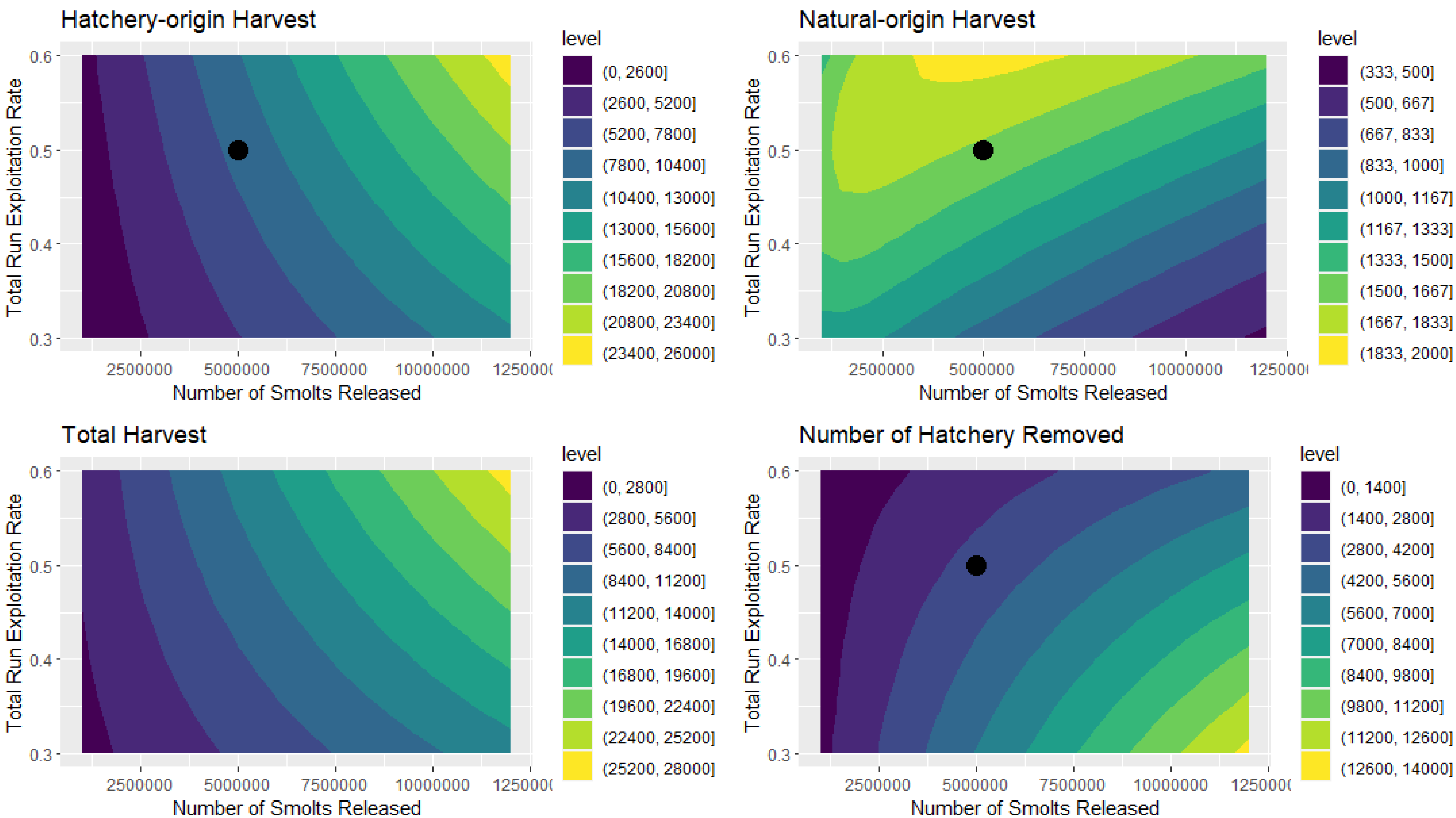

Figure 9. Same basic format as Figure 3 except here the contour plots show the effects of different exploitations rates (y-axis) and smolt releases (x-axis) on harvest of hatchery-origin fish (upper left), harvest of natural-origin fish (upper right), total harvest (lower left; this repeats the upper right plot from Figure 3), and the number of hatchery-origin returns that are removed as surplus, died prior to spawning, and removed in the river at a weir (lower right). For these results natural-spawning capacity = 4000 and selection = moderate.

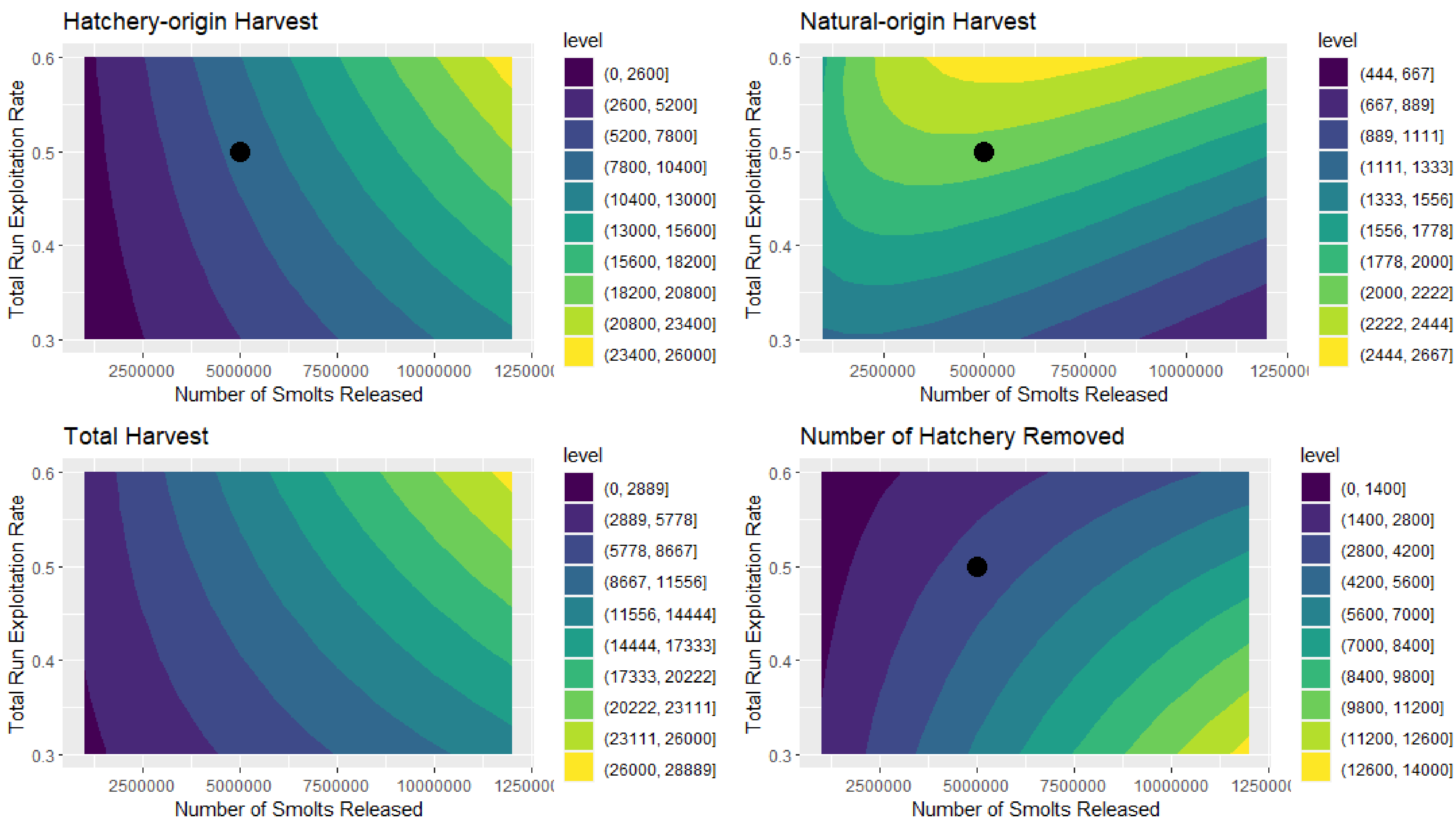

Figure 10. Same as Figure 9 except selection = weak.

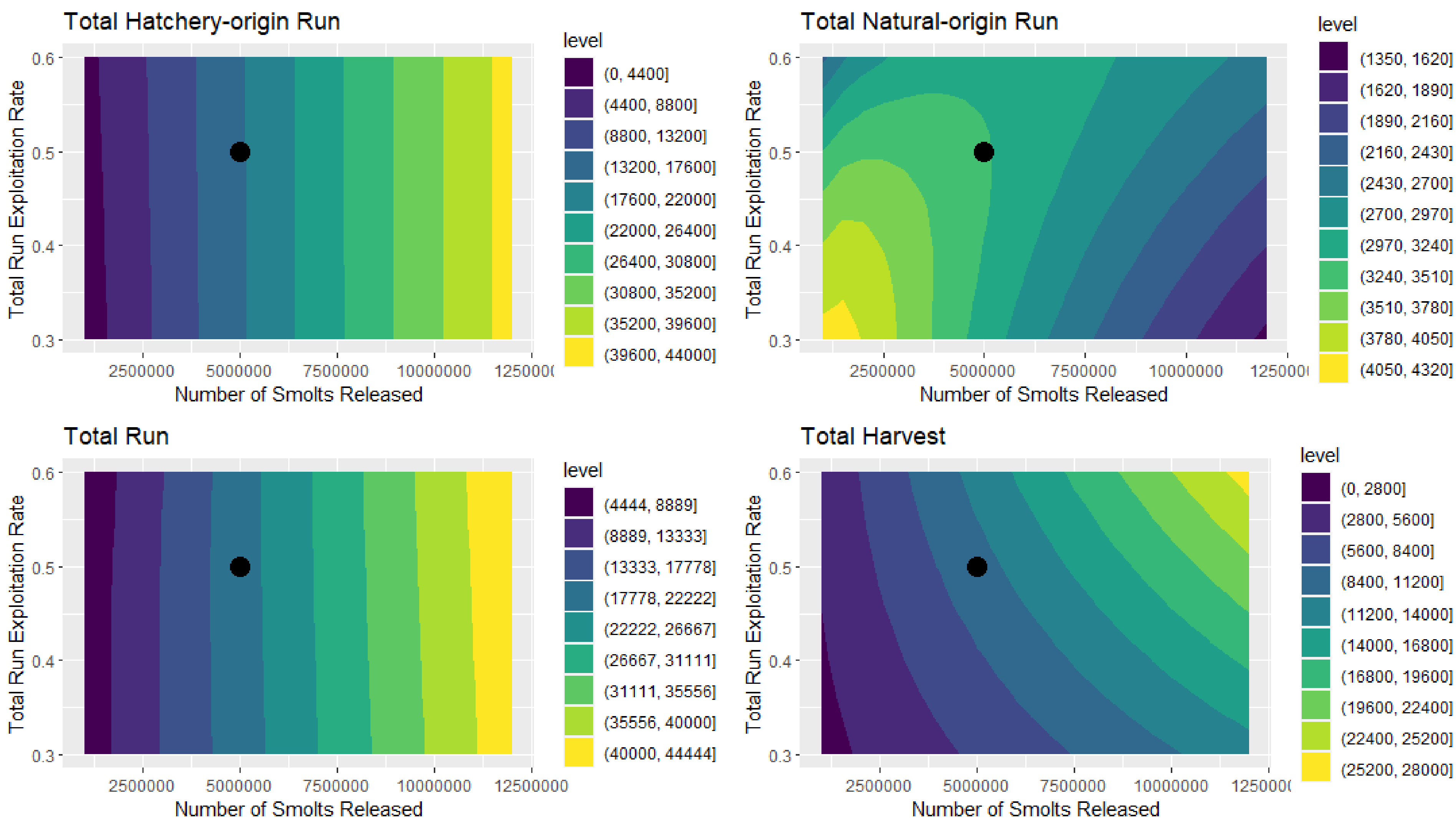

Figure 11. Same basic format as Figure 3 except here the contour plots show the effects of different exploitations rates (y-axis) and smolt releases (x-axis) on hatchery-origin run prior to harvest (upper left), natural-origin run prior to harvest (upper right), total run prior to harvest (lower left), and total harvest (lower right; this repeats the upper right plot from Figure 3). For these results natural-spawning capacity = 4000 and selection = moderate

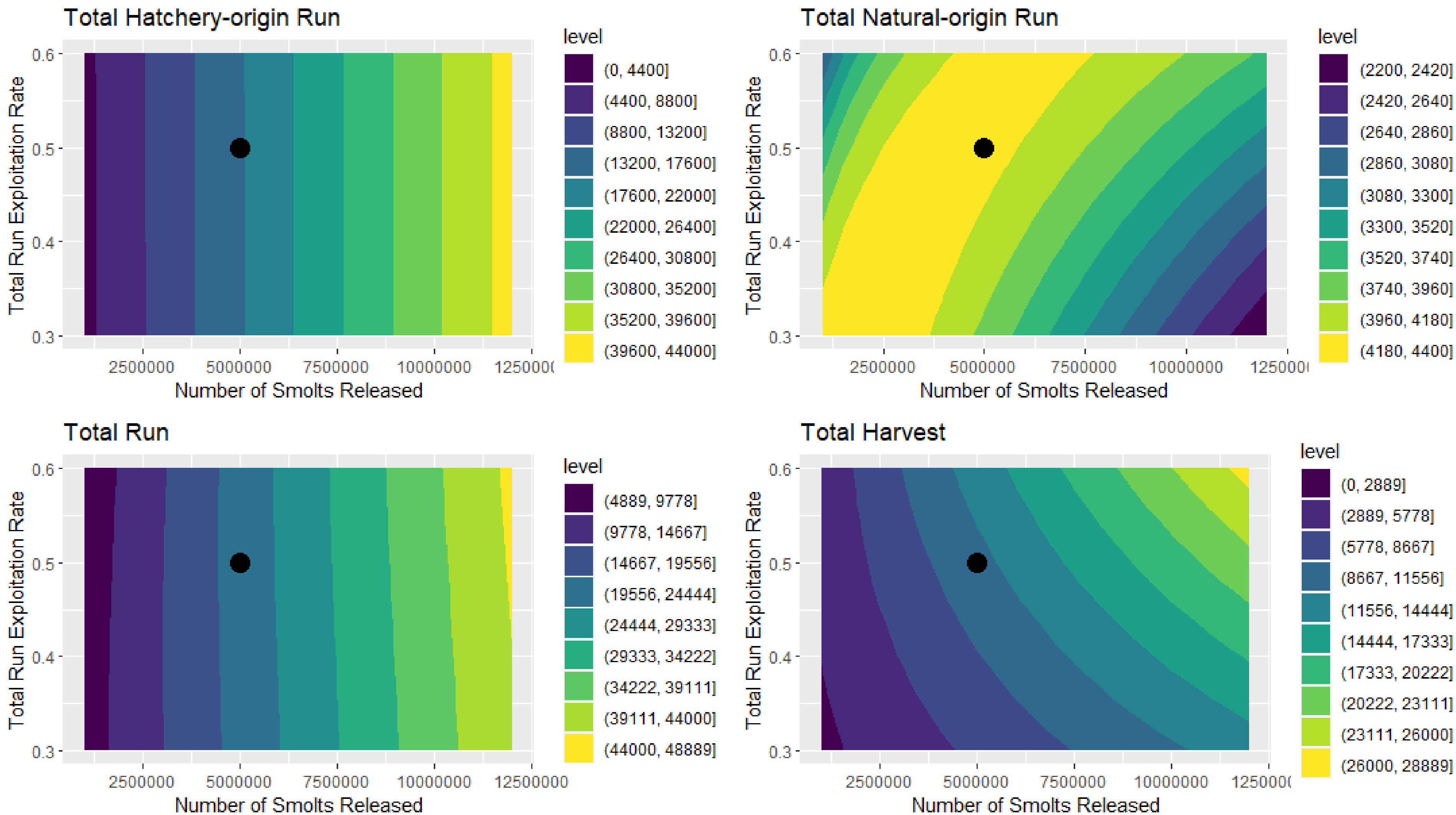

Figure 12. Same as Figure 11 except selection = weak.