Testing the Concept of an Optimal Stability ‘Window’

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Abstract. The effects of the interplay between light and macronutrient supplies on oceanic primary production leads to the concept of an optimal stability window (Gargett 1997). When coupled with expected oceanic effects of extreme phases in variation of the winter/spring atmospheric circulation in the North Pacific, this concept results in a possible explanation for observations of (1) correlation between overall North Pacific salmon stock size and strength of the Aleutian Low Pressure system and (2) anti-correlation between northern (Alaska) and southern (Oregon and northern California) stocks within the eastern Pacific. This paper addresses the question of hypothesis testing.

1. Introduction

The study of effects of climate variation on fisheries has depended heavily upon correlations between fisheries data, generally catch, and some environmental variable(s). While such correlations are suggestive, reliance upon them as predictive tools is an uncomfortable state of affairs - if we have no idea of the mechanistic connections between the variables being correlated, we can’t have much confidence that the correlations will continue, and indeed they often don’t (see Welch, this volume, for an example).

It is now essential to move on to a next stage, in which two things will happen. First we will use correlations less as predictive measures and more as clues which signal and constrain possible mechanistic connections. Secondly, we will seek to test hypothesized connections through a variety of means: with retrospective analysis of existing historical data, with coupled biophysical numerical models, and with short-term observational programs which have been motivated by data/model results and will be directed to specific process linkages.

As an illustration of the first stage of this process, we will use the proposal of an optimal stability window as a possible mechanism to explain observed correlations between the strength of the wintertime Aleutian Low pressure system and North Pacific salmon stocks. The discussion of this mechanism will be brief, as a more detailed description is available (Gargett 1997). The focus here is on the next step - testing.

2. The Optimal Stability Window

The optimal stability window was proposed as a mechanistic explanation of two correlational clues, depicted in Figure 1 - first, the positive correlation suggested by Beamish and Bouillon (1993) between North Pacific all-nation salmon catch (interpreted as a measure of survival) and an index of the average strength of the wintertime Aleutian Low pressure system; second, an anti-correlation between the survival rates of northern (Alaska) and southern (Washington, Oregon and northern California) stocks, demonstrated by Francis and Sibley (1991) and suggested here by anecdotal information extracted from the trade magazine Pacific Fisherman by Mantua et al. (1997).

Figure 1: A positive correlation is observed between the total North Pacific salmon catch (dashed line) and an index of strength of the winter-time atmospheric Aleutian Low pressure system (ALPI: the Aleutian Low Pressure Index of Beamish and Bouillon 1993). Anecdotal information abstracted (Mantua et al. 1997) from Pacific Fisherman suggests that this correlation is out-of-phase between northern and southern stocks.

Salmon survival rates appear to be determined mainly during the first year of ocean life (Francis and Hare 1994). This year is spent predominantly in coastal waters (Hartt and Dell 1986), so the mechanism setting survival apparently operates in the coastal ocean, rather than the deep sea. The optimal window mechanism assumes that the survival of juvenile salmon is determined by their (zooplankton) food...
supply while transiting the coastal ocean, and that the zooplankton supply is in turn set by the level of primary production (phytoplankton supply). Thus the connection between atmospheric and/or oceanic conditions and salmon survival rate comes through the effect of physical processes on primary production in the coastal ocean.

Water column stratification (stability) is a characteristic of the physical ocean environment which strongly influences levels of primary production by modifying the strength and effects of turbulent motions in the surface layer. Because vertical motions are suppressed by water-column stability, turbulence in regions of strong stability is characterized by vertical displacements and associated vertical fluxes which are smaller than those in more weakly stratified environments. The upper ocean environment of light and macronutrients necessary for marine plant growth is determined by these small-scale turbulent motions, acting within large-scale modulation of both the light field (through north/south location) and the nutrient field (by gyre-scale positioning of the subsurface nutrientcline). When turbulent motions are damped by stratification, re-supply of necessary nutrients decreases but average light increases; in contrast, regions of low stratification will be well-supplied with nutrients but average light will decrease as phytoplankton are moved over larger vertical distances. Within some intermediate range of stabilities, both nutrient and light supplies are sufficient (the optimal window shown in Figure 2). In upwelling subpolar gyres at high latitudes, macronutrients are not limiting but primary production is light-limited during at least part of the year. In downwelling subtropical gyres at low latitudes, light is plentiful but macronutrient levels are low. It thus seems reasonable that northern (N) and southern (S) phytoplankton populations exist towards opposite ends of the optimal window, as shown schematically in Figure 2.

Now if stability were to increase everywhere around the coastal rim of the North Pacific, N populations move into the window, while S ones move out, and vice-versa, as shown in Figure 2. Such changes in stability will clearly provide out-of-phase variation between N and S phytoplankton stocks, hence in salmon survival. Gargett (1997) argues that variation between strong and weak phases of the Aleutian Low produces such in-phase changes in coastal stability, through coupled variation in freshwater input to the subpolar coastal ocean and wind-driven upwelling in the subtropical coastal ocean. In addition, the associated changes in stability are such that N stocks thrive during periods of strong Aleutian Low, as observed.

3. Testing the Optimal Stability Window Hypothesis

The main purpose of this paper is to consider some of the ways in which one might try to test this hypothesis, thereby demonstrating both the difficulties experienced and hopefully, some of the new insights which may be gained during the attempt.

3.1. Retrospective data analysis

One can first ask whether existing information which has not been used in formulating a mechanistic hypothesis is consistent with resulting predictions. In the present context, the question is whether existing records of coastal ocean stability demonstrate the postulated variation relative to salmon catch records.

For mechanisms which operate over decadal time scales, retrospective testing requires data over similar time scales. When we look for a water-column property like stability, most well-sampled coastal ocean time series go back “only” 20 years. While this is a large fraction of an individual scientist’s working lifetime, it is only about a half-“cycle” of the variations in salmon catch shown in Figure 1. We’ve explored the possibility of obtaining long time series from CTD/bottle data inventories, using a test area in the north-east Pacific just off the mouth of Juan de Fuca Strait (Figure 3). This area is as well-sampled as any region of the BC coast, because it includes the inner end of “Line P”, a line of stations sampled a minimum of 3-4 times per year since 1956, as well as part of a more recent coastal project (La Perouse). Density profiles have been abstracted for a “spring” season defined as April-May-June, when phyto plankton growth should set the table for larval salmon first entering the ocean.
Variability in near-surface stratification has been roughly quantified over the entire length of the available time series by differencing densities averaged over an upper layer of 0-20 m and a lower layer of 60-80 m. Values of upper (+) and lower (o) layer densities from individual profiles are shown as symbols in Figure 4(a): lines connect the “spring” averages over the (variable) number of available stations. Figure 4(a) illustrates the lack of continuity in the available time series - a decade gap over the 1940s, other minor gaps later - as well as the frequent sparsity of data points in earlier years which do have data. While the density difference (“stratification”) record (Figure 4(b)) is predictably noisy, especially before the increased sampling density in the early 1980s, there does appear to be a suggestion that stratification was higher during the 1980s when northern stocks produced very large catches. However, the most obvious signal is a major event encompassing 1959 and 1960, associated with a major decrease of surface layer density (due primarily to a decrease in salinity). Such a large increase in stability ought to have had major effects on fish stocks in the ocean hypothesis - however before looking at fish records, let’s first look more closely at the reliability of the event in the physical data. First consider data density and distribution. The 1959 and 1960 averages include 6 and 3 stations respectively - of the 6 in 1959, 2 were taken within 1 hr of another in the same location, hence are effectively duplicate data. Of the remaining independent data points, 2/4 and 2/3 respectively are located within the 100-m depth contour, so the averages may be more highly weighted to very near-coast conditions than averages from years with more samples and/or more homogeneously distributed samples.

While the previous discussion highlights problems associated with comparing data which are sparsely and inhomogeneously distributed in both time and space, it doesn’t necessarily negate the occurrence of a high-stability event in near-coastal waters in 1959-60. Before finally accepting this as evidence of a major increase in surface layer stability, however, we pause once more to look for corroborating data. If surface-layer density decreased over a spatially significant area by the amount indicated in Figure 4(a), this change should be clearly evident in the time series of density calculated from T and S measurements at the Canadian network of lighthouse shore stations along the west coast of Vancouver Island. Figure 4(c) shows the time series of surface layer density superimposed (offset by one unit in sigma-t) on that of averaged spring-season density from the Kains Island and Amphitrite Pt. lighthouses, locations shown in Figure 3. While the two time series show similar decreasing trends in surface layer density since about 1970, and the 1960 values are not far apart, the 1959 averages differ by over one sigma-t unit. This difference seems excessive, and suggests that even when older water column data exist, there may be problems with data quality (methods) as well as amount and distribution. It is certainly unwise to base conclusions on composite water property time series without sources of corroborating data. The overall conclusion is that time series of water column stability for use in testing the window hypothesis probably cannot be obtained reliably from the historical bottle/CTD data base: problems of sampling frequency, spatial distribution, and relative quality seem insurmountable. This situation will change if the sampling density seen in the final 15 years of Figure 4(a) can be maintained over the decades.
which characterize major variation in the North Pacific ocean/atmosphere system.

However, even were such data density available for a much longer time, the BC coast is not the best place in which to look for clear evidence of the optimal window effect. Why? Because coastal BC waters are a complicated mixture of “pure” N and S regimes (Figure 5(a)). Studies of anomalous precipitation associated with extreme states of the Aleutian Low (Cayan and Peterson 1989) indicate that an amorphous “boundary” between anomalously high and low winter precipitation lies somewhere between the Queen Charlotte Islands and Alaska: thus precipitation affecting major southern BC stocks, such as those from the Fraser River, may actually be out-of-phase with the precipitation in the “pure” N regime. Secondly, the southern BC outer coast is affected by seasonal (summer) upwelling rather than the year-around upwelling characteristic of a “pure” S regime. The mixed transitional nature of BC coastal waters suggests that for the clearest signature of a relationship (or lack thereof) between coastal stability and salmon survival, we should be looking for data from Alaska (N) and northern California (S) coastal waters. Lacking sufficient water-column data over the required decades, it is necessary to look in historical data for surrogates for stability in these regions. If we may assume that deeper waters are essentially constant over decadal time scales (a big “if” - see lower layer density time series in Figure 4(a)), perhaps it is possible to use surface temperature in the S and surface salinity in the N as such surrogates. Unfortunately, while reasonably long time series of sea surface temperature are available from coastal shore stations in the S, in the N there are no time series of ocean surface salinity comparable in length to those from the BC coast, pretty much the minimum length necessary to cover a full cycle in fish stock abundance. It would thus be necessary to step even further back from a direct determination of stability in the N region, employing surrogates (like air temperature or stream flow) for the already surrogate surface salinity: this effort becomes increasingly tenuous.

It appears that the most conclusive way to test the optimal window hypothesis is to install a repeated CTD site, equivalent to the Alaskan GAK1 station, off northern California and then wait 30 years - are there any shorter term possibilities?

3.2. Models and focussed process observations

The mechanisms underlying the “optimal window” hypothesis should operate on interannual as well as interdecadal time scales. Thus process models of smaller parts of the system on shorter time scales should enable us to explore various predictions of the window hypothesis (or others) without waiting 30 years for results. As an example, consider the Strait of Georgia (Figure 3), the region of first ocean contact for Fraser River salmon stocks. What does the window hypothesis predict for this region? As mentioned previously, at times when Alaska is wet, southern BC is dry (Figure 5(a)); thus an assumption that the Strait of Georgia is a Northern (light-limited) region would lead to a prediction that Fraser stocks should vary out-of-phase with northern BC and Alaskan stocks. However, because of the enormous amount of freshwater delivered to the semi-enclosed Strait during spring freshet of the Fraser, the surface layer regularly becomes nutrient-limited in the late spring/early summer period when juvenile salmon first enter the sea - thus the Strait is actually a Southern regime, in the sense that its spring/summer primary production is nutrient-limited (Figure 5(b)). Lower freshwater input associated with strong Aleutian Lows results in lowered stability, moving primary production towards more favorable conditions (Figure 5(c)): the opposite is true when the Aleutian Low is weaker than average (Figure 5(d)). The window hypothesis thus predicts that Fraser stocks which enter the Strait during favourable conditions (associated with strong Aleutian Lows) and migrate northwards (where conditions continue favourable), should be strong when N stocks are strong. This prediction agrees with observations for the dominant Fraser River sockeye stocks (Beamish et al. 1997) – but is the mechanism correct?

![Figure 5](image-url)
channels (henceforth H) shown as ‘Haro Strait’ in Figure 3, then the broad Juan de Fuca Strait (henceforth J). We feel that such a model, minimalist in both physics and biology, is (1) an essential tool for exploration of parameter sensitivities, (2) an appropriate first step in the study of decadal time scales (more complex models being too expensive to run), and most seriously perhaps (3) the maximum degree of model complexity that is constrained by presently available data.

The estuarine box model (Figure 6) is forced by seasonally variable freshwater flux QF into the upper (0-50 m) G box, with salinity balance maintained by restoring the salinity of the deep (50-200 m) J box to a “Pacific” value SP which varies seasonally as summer upwelling moves more saline water onto the BC shelf (Freeland and Denman 1982). Within the H boxes, strong tidal mixing has an imposed spring/neap variation, resulting in spring/neap pulsing of water properties and estuarine flows (Figure 7(a)).

With choices for QF and SP based on observations, the single exchange coefficient determining the density-driven flow can be chosen to reproduce the seasonal variation of salinities in all 6 boxes (Figure 7(a)). These seasonal variations are reasonably well-known (at least compared with information available on biological variability!). A simple N(nitrate)-P(phytoplankton)-Z(zooplankton) model (see Appendix) is then coupled to this physical model, and with reasonable choices of biological parameters, leads to an acceptable picture of the biological cycles in the system (Figure 7(b)). In G, a spring bloom initiated by increasing light level is followed by a minimum caused partly by nutrient limitation and partly by Z grazing; a secondary late-summer peak of P occurs as N levels are renewed by advective input from offshore upwelling (note that N in the lower layer of J is restored to an imposed seasonal cycle, of form identical to that of SP, and magnitude consistent with the deep salinity/nitrogen relationship shown or this region by Mackas and Harrison 1997). Levels of P are much lower in H, where strong vertical mixing causes periodic losses to the

Figure 6: Schematic of a box model of the Strait of Georgia, which is connected to the Pacific Ocean primarily through Juan de Fuca Strait and a complex of tidal passages (referred to here as “Haro Strait”) characterized by strong tidal mixing. An estuarine circulation, modulated by tidal mixing, is forced by freshwater input QF (dominated by Fraser River runoff in early summer) to the upper Strait of Georgia, and by a return flow of water of “Pacific” salinity (SP) which usually occurs in late summer.

Figure 7: (a) Annual cycles of physical fields output by the GHF box model under a steady annual forcing cycle in Fraser River flow QF and Pacific deep salinity SP (upper panel): adjustment from uniform initial salinities occurs within a single year. Stability, represented by the difference $S$ between upper and lower box salinities, is maximum in G and minimum in H, as observed. Salinity ranges predicted for all 6 boxes agree reasonably well with observations, which are sufficiently numerous to serve as real constraints. The bottom panel shows the horizontal estuarine flows driven by differences in density between the (upper) boxes; these flows are modulated by the spring/neap mixing cycle in H.

Figure 7 (b) Annual cycles of biological variables from an NPZ model coupled to the physical system of (a). The upper panel shows the N cycles in all 6 boxes: note the period of N-depletion in G following the spring peak of P. The other 3 panels show upper layer values in the three regions; line width is fine for N, medium for P, and heavy for Z. While a strong spring “bloom” of P in G and much lower values of P in H provide a generally acceptable picture, the nutrient and biological fields are substantially less constrained by observations than are the salinity fields of (a).
(same as Figure 7(a)). In particular, Figure 9 shows the parameters while keeping the physical forcing fixed, now the effect of varying some of the biological dependent upon variation in physical forcing. Consider have seen that the productivity of $G$ was not strongly correlated with atmosphere/ocean variability on decadal time scales, with the same phase as $N$ stocks – if the optimal window hypothesis is not the explanation, what is? Simple models allow us not only to disprove hypotheses, but also to explore other possibilities. We have seen that the productivity of $G$ was not strongly dependent upon variation in physical forcing. Consider now the effect of varying some of the biological parameters while keeping the physical forcing fixed (same as Figure 7(a)). In particular, Figure 9 shows the

unlit lower layer. $J$ shows levels of both $P$ and $Z$ standing stock which are slightly higher than $H$, but still much less than $G$. This situation can then be perturbed by allowing significant parameters describing the physical forcing to vary within bounds which are, again, reasonably well determined from observations. As can be seen in Figure 8(a), stochastic forcing of the physical system can produce variations of up to a factor of 2 in $G$ stability (−$S$). However (Figure 8(b)), this variation does not produce a comparable variation in $P$ or $Z$ standing stock in $G$; i.e., weaker stron$ger$ stratification does NOT produce significantly larger (smaller) supplies of food (Z) for juvenile salmon. The optimal window idea does NOT apply to this system, at least if the physical dynamics of the system are those incorporated in the box model - and the reason lies within these dynamics. Because the Strait of Georgia is modelled here as a strongly estuarine system, nutrient supply to its euphotic zone is dominated by density-driven advection rather than by the local stratification-modulated mixing processes upon which the window hypothesis was based.

However Fraser River salmon stocks do vary dramatically, and the variations are apparently correlated with atmosphere/ocean variability on decadal time scales, with the same phase as $N$ stocks – if the optimal window hypothesis is not the explanation, what is? Simple models allow us not only to disprove hypotheses, but also to explore other possibilities. We have seen that the productivity of $G$ was not strongly dependent upon variation in physical forcing. Consider now the effect of varying some of the biological parameters while keeping the physical forcing fixed (same as Figure 7(a)). In particular, Figure 9 shows the

Figure 8: (a) The GHF box model is here forced by the stochastic fields of QF and SP shown in the upper panel: (random) variations allowed in the magnitude, time extent and timing of QF, and in the magnitude, time extent and delay (relative to QF) of SP are consistent with observed natural variability in these features. The resulting stability in $G$ varies by approximately a factor of 2.

Figure 8 (b) Annual cycles of the NPZ fields associated with the stochastic model run. Line width conventions are the same as Figure 7(b). While interannual change in $P$ and $Z$ standing stock in $G$ is discernible, the magnitude is much smaller than the factor of 2 change in stability which occurs in the physical system. Thus the optimal stability window mechanism apparently cannot explain substantial variations in productivity in the Strait of Georgia: reasons are discussed in the text.

Figure 9: Major changes in $P$ and $Z$ standing stock in $G$ can be associated with minor changes in parameters describing the biological sub-system. When physical fields are identical to those shown in Figure 7(a), and zooplankton mortality rate is increased by approximately 12% over that used in generating Figure 7(b), the box model produces the fields shown here: note that in $G$, $P$ remains nearly constant through the year, and $Z$ standing stock is extremely low. (Line width conventions are the same as Figure 7(b).)
result of increasing the Z mortality rate by 12% over that of Figure 7(b). The result is a completely different mode of biological production, in which the P stocks of G are released from grazer control and remain at a nearly constant intermediate level, save for a brief mid-winter period when light is limiting. Z stocks within the upper Strait remain at a low level throughout the year. Reduced grazing pressure also allows the P stock in J to achieve much higher levels (note change of P scale between Figures 7(b) and 9), producing a much larger summer drawdown of surface layer N.

While quantitative details vary, in a qualitative sense the GHF system appears to have two distinct and stable modes, dependent upon particular combinations of biological parameters. Are these modes simply artifacts of the simplicity of the biological component of the box model or may the real Strait of Georgia actually behave like this? It is at this point that we begin to appreciate the dearth of appropriate observational data with which to validate the results of biological models, whether such results come from simple and cheap box models like this one, or from much more complex and expensive models with high spatial resolution and more “realistic” biology. In the entire GHF system, there are very few measurements of annual cycles of even nitrate, much less phytoplankton and/or zooplankton biomass, much less measurements of interannual variability of these quantities. For the GHF system, there are only fragments of the kind of data which is needed for model validation. Figure 10 shows results from Stockner et al. (1979), who took monthly samples of P and Z in the Strait of Georgia for 2 years in the mid-1970s. These 2 years do appear to hint at the reality of (at least) 2 modes of production – one (1975) in which both P and Z are strongly peaked in spring, and another (1976) in which P stocks remain at a more constant level throughout the light season and Z levels are low. Clearly, however, much more observational data is needed before we may have confidence in the reality of biological mode shifts.

Investigation of the GHF biological/physical system, as represented by our box model, leads to important conclusions:

1. Reasonable variability in physical forcing does not translate directly into large changes in Z standing stocks, hence cannot be a direct cause of large variation in juvenile salmon survival rates based on food availability, à la “optimal windows”.
2. Small changes in biological parameters may produce “mode-switching” of the system between states of high and low Z standing stock in G.
3. If the physical environment does produce a significant effect on the output of the biological system in G, it apparently does so indirectly, through the effect(s) of physical processes on biological rate parameters.

In future, the box model will serve as a useful “toolbox” for examining mechanisms by which features of the physical environment may mediate critical biological rate parameters.

4. Summary and Conclusions

This paper has looked at the various means available for testing the idea of an optimal stability window (Gargett 1997) as a mechanistic underpinning for observed correlations between North Pacific salmon catch and variation in atmospheric forcing of the ocean. We conclude that this idea cannot be tested using historical CTD/bottle data sets: problems of data density (in both time and space) and relative quality make it extremely difficult to form reliable time series of water-column stability over the required decadal time scales, even in “well”-sampled regions. It also appears that the use of surrogate time series of (upper-layer) shore station data (Gargett 1997) will be unsatisfactory for two reasons; first, one is forced to use a surrogate for a surrogate in the N, where long time series of surface salinity are not available; second, the assumption of constant lower-layer properties appears to be unfounded, at least in the BC coastal area which we have examined. (Dis)proof of the window mechanism from water column properties must await the maintenance/establishment of repeat CTD stations in the coastal ocean at the N and S limits of the range of North Pacific salmonids, and another full “cycle” of decadal variation in atmospheric forcing.

Not wishing to wait this long, we have suggested that even very simple models of interannual variability of the biological/physical system in smaller domains may provide important tests of the window hypothesis; in the case we addressed, it failed. Nonetheless, the focussed process of testing provided a framework for understanding why it failed (in what way the physics of the system differed significantly from that underlying the window hypothesis) and for exploring additional mechanistic ways in which the physical
environment could affect biological productivity of the system.

In the end, it is to be hoped that the hypothesis of an optimal stability window will provide a focus for additional efforts towards understanding the actual processes by which physical processes affect biological production in the ocean, and furthermore, that efforts to test specific mechanisms will provide impetus for improving the woefully inadequate data base presently available for validating even the simplest model which attempts to describe even interannual, much less decadal, variability of ocean ecosystems.

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Appendix:

Concentrations of the biological variables N, dissolved nutrient, and P and Z, respectively phytoplankton and zooplankton biomass in units of nitrogen, are determined by integrating the following N-P-Z model equations (with the addition of advective terms resulting from the estuarine circulation and diffusive terms resulting from tidal mixing; further details of the physical/biological models may be found in Li et al. (1998a,b)):

\[
\frac{\partial P}{\partial t} = rP \min\left(\frac{N}{K_N + N}, \frac{1}{i_b + 1}\right) - r_m \frac{P^2 Z}{K_p^2 + P^2} - p_m P, \quad (1)
\]

\[
\frac{\partial Z}{\partial t} = g_a r_m \frac{P^2 Z}{K_p^2 + P^2} - z_m Z, \quad (2)
\]

\[
\frac{\partial N}{\partial t} = -rP \min\left(\frac{N}{K_N + N}, \frac{1}{i_b + 1}\right) + \alpha \left[1 - g_a \frac{r_m}{K_p^2 + P^2} + p_m P + z_m Z\right]. \quad (3)
\]

Here phytoplankton grow at maximum rate \(r\), but may be limited by either nutrient (N) or light (I), described by Michaelis-Menten functional forms with half-saturation constants \(K_N\) and \(i_b\) respectively. Zooplankton grazing is described by a nonlinear (Holling III) function of phytoplankton concentration, with maximum grazing rate \(r_m\) and half-saturation constant \(K_p\). Other constants are: \(g_a\), zooplankton grazing efficiency; \(p_m\) and \(z_m\) respective mortality rates of phytoplankton and zooplankton (the latter including predation losses as well as natural mortality); and \(I\), the fraction of total plankton losses which are immediately recycled back to the nutrient (N) pool.

The simulations shown in Figs. 7 and 8 use constant values of: \(r = 0.25 \text{ d}^{-1}\), \(K_N = 1.5 \text{ mmol N m}^{-3}\), \(i_b = 50 \text{ W m}^{-2}\), \(r_m = 0.1 \text{ d}^{-1}\), \(K_p = 1.5 \text{ mmol N m}^{-3}\), \(g_a = 0.75\), \(p_m = 0.025 \text{ d}^{-1}\), \(z_m = 0.040 \text{ d}^{-1}\), and \(I = 0\). The results of Figure 9 are obtained by increasing \(z_m\) to 0.045 d\(^{-1}\).

References


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