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THREE TANK MODEL

A Top down or bottom up dominance analysis

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Abstract: The author proposes a simple mechanical model of biomass flow in an ecosystem using a hydrological model. Three tanks representing three trophic levels to determine which form of control is predominantly effective and under what conditions. The model shows that in the question of which is the dominant control, the cascade processes of control from top (predator control) or from bottom (Prey control), Top down control is predominant when the system is predator efficient, where mortality due to intraspecific competition is steady and bottom up control is predominant in systems where the predators are inefficient and mortality due to intraspecific competition is varying dependent on resource levels. The behavior of trophic levels under each type of control is also discussed.
Keywords: biomass flow, predator controlled flow, resource controlled flow, competent predation, incompetent predation.

INTRODUCTION:

The influences of top down and bottom up control has been suggested to be based on spatial scales (Seitz, R. D. and Lipcius, R. N.), on the type of ecosystem, (Lee A. Dyer, A.L and Letourneau, D., 2003), Behavior moderated, (Beckerman et al, 1997) and even shown to be regulated by Body mass in certain discussions.

It is however apparent that though every one of the arguments have their validity, they are partial solutions and have exceptions and the flow of control is dependent on a combination of all these elements.

To establish the importance and extent of influence of these elements, a comprehensive theoretical model or simulation is required since a comprehensive and complete empirical study of trophic levels in an ecology is a difficult undertaking given the extreme complexity of even the smallest ecological system.

Such studies are further made difficult when physically large systems are under study and the difficulty is compounded when the ecological system is not completely isolated. Biomass measurements an flow from one trophic level to the next is next to impossible to gauge accurately.

Considering a single trophic level, it is elementary that some biomass perpetually flowing in from the resource trophic level while some biomass is flowing out, a portion of it to the next immediate trophic level while the remaining portion flows out to a more distant decomposer level. For the sake of simplicity, the second outflow of biomass can be considered to be made of two parts. An absolute minimum level due to death by natural causes and the remaining mortality due to competition for resources.

Based on this simple model, a mechanical model can be constructed to simulate biomass flow through trophic levels.

THE MODEL:

Construction:

The model consists of a series of tanks arranged one below the other. The volume of the tanks is in descending order (The highest tank being the largest). Water flows from the top tank through outlets at the bottom Three tanks or trophic levels chosen for the model is the optimum number required to analyze the effect of top down and bottom up controls.

Each tank has two outlets. Outlet *a* and outlet *b*. Each outlet has the water flow through it regulated by means of valves. These valves are controlled by floats in the tanks.

Valve *a* of each tank is controlled by the level of water in the tank above it (preceding) while valve *b* is controlled by the level of the water in the given tank itself.

The water from the last tank and outlets *a* flow into a large basin from which the water is re-circulated to the 1^{st} tank.

The Analogy:

The model is intended to simulate the flow of biomass from one trophic level to the next. The content of each tank or trophic level in the model does not distinguish horizontally between the variety of species in a given trophic level but instead represents the gross biomass present in each trophic level in the given ecosystem. However the model can also be taken to depict local single species loops in an ecosystem.

The volume of the tanks represents the density carrying capacity of each trophic level. While applying the model on a species level, the volume of the tank will be modeled on the most restrictive density dependent parameter that the trophic level or species under consideration is subject to.

Consumption of resource which is the biomass available from the previous trophic level is simulated by the flow of the water from the tank above it.

Since the amount of resource consumed by any given trophic level is directly proportional to the biomass of the given trophic level in a top-down control (The biomass of prey consumed is assumed to be directly proportional to the biomass of predators) the flow of water from the resource trophic level to the given trophic level is to be controlled by the level of the water in the trophic level under consideration.

This is simulated by the use of a float in each tank. Increase in the water level will increase there height of the float which pushes open the outlet valve of the resource tank further increasing the flow. Reduction of water in the given tank will bring the float lower thereby closing the valve and reducing the water flow from the resource tank.

In the same way that the component species of the given trophic level consume prey from the previous trophic level, the consumption of the given trophic level by the next trophic level (predator) is simulated by the outlet vale through which the water is fed into the next trophic level. (represents mortality due to interspecific competition in resource trophic level) The flow of water through this outlet is controlled by the level of the next trophic level in the same manner that this trophic level controls the outlet for the previous trophic level.

Outflow of biomass from a trophic level is not only through predation but also through competition for resources and natural or accidental death.

Since resource competition can be considered indirectly proportional to resource availability, i.e., resource competition or death due to resource competition increases when resource availability decreases and vice versa, for the given tank, the second outlet valve is controlled by its previous tank (resource) such that increase in resource tank level closes the valve reducing the outflow of water and decrease in the resource tank opens the valve flow increasing the outflow of biomass from the trophic level. (represents mortality due to intraspecific competition)

Though the model is based on three trophic levels, any number of trophic levels can be incorporated within the same inflow and outflow regulating mechanisms.

The above model closely depicts an island ecosystem. For an open ecosystem, each trophic level can be considered to include a biomass inflow from unspecified source and redefined outflow corresponding to immigration and emigration.

That is however outside the scope of this study and is not considered here.

Method:

We examine the behavior of trophic levels under the influence of the two types of controls by simulating extreme conditions. That is, strictly only one type of control is active. We test the model for a pure top down control with two cases. Increase in biomass of the top tropic level, decrease in biomass of the top tropic level. Similarly we also test the model with pure bottom up controls for increase in the biomass of the lowest tropic level and decrease of biomass of the lowest tropic level. .

A third test is to observe the reaction of the trophic levels under the same conditions with opposing initial changes. That is, we test the behavior of a bottom up controlled system with a change in the top tropic level and a top down controlled system with a change in the lowest trophic level.

We also test the behavior of tropic levels by altering the biomass level of an intermediate tropic level both ways (Increase and decrease) in both type of cascades.

From the results, it is easy to establish on general terms, the conditions under which each type of cascade control exists.

RESULTS

PURE BOTTOM UP CONTROL

Condition:

(1) Resource availability limits or increases trophic level biomass. That is, the level of biomass in a given a trophic level is controlled by the level of biomass in the trophic level immediately preceding it.

(2) The level of the biomass in the considered trophic level does not regulate the level of the biomass in the trophic level preceding it. It regulates the level of biomass in the trophic level succeeding it.

In terms of the model;

(1) Only bottom up controls are active

(2) Top down controls are absent. Flow of water from one tank to the next is fixed and unregulated.

(3) The gross outflow/ gross inflow ratio is assumed to be 1 in the initial condition prior to change. That is, the biomass at the considered trophic level is steady.

Case 1: Increase in resource

(a) Trophic level 1 is increased.

(b) Increase in trophic level 1 causes the float to close the outlet valve of trophic level2.

(c) The change in the ratio of inflow to outflow in favor of the inflow rate causes the increase of trophic level 2
(d) Increase in trophic level 2 closes the outlet valve of trophic Increase in trophic level 3
(e) The change in the ratio of inflow to outflow in favor of the inflow rate causes the increase of trophic level 3
(f) All trophic levels reach maximum density level and reach new equilibrium determined by the density dependent parameters governing population density level. This condition is probably the most common ecosystem found recorded and researched. (Batzli, G.O., 1983) (Caughley, G and Lawton, J.H, 1981.) (Ho, Chao-Pao, Huang, Shy-Tyng 2001) (Holmgren et al 2001)

Case 2: Decrease in resource:
(a) Trophic level 1 decreases.
(b) Decrease in the tropic level 1 causes reduced inflow to trophic level 2 and increased outflow through resource competition (Increased outflow due to higher mortality as a result of decreased resource). As a result, gross outflow exceeds inflow. Eventually trophic level 2 is extincted.
(c) The same process is repeated in tropic level 3.

Top down variation in pure bottom up control:
In an ecosystem that has pure bottom up control, consider the effects of variation at the top.
Variation in trophic level 3; Increase or decrease in trophic level 3 does not change the outflow level of trophic level 2 as the level of biomass does not control either inflow or outflow rates of trophic level 2. By default, it also does not affect trophic level 3.
If trophic level 2 is destabilized; Decrease in tropic level 2 changes only the outflow rate of trophic level 3, increasing it. Higher outflow to inflow rate causes the biomass in trophic level 3 to reduce along with the reduction of trophic level 2 to zero.
Trophic level 1 remains unaffected since neither its inflow or outflow is controlled by the biomass in trophic level 2.
Increase in trophic level 2 reduces the outflow of biomass from trophic level 3 thereby increasing the biomass of trophic level 3 till the density threshold is reached after which the biomass remains fixed at the threshold limit.
Again the biomass of trophic level 1 is unchanged since neither its inflow nor outflow are affected by the changes in trophic level 2.

PURE TOP DOWN CONTROL:
Condition:
(1) Predation limits or increases trophic level biomass. That is, the level of biomass in a given a trophic level is controlled by the level of biomass in the trophic level immediately succeeding it.
(2) The level of the biomass in the considered trophic level does not regulate the level of the biomass in the trophic level succeeding it. It regulates the level of biomass in the trophic level preceding it.
In terms of the model;

(a) Only the top down control valves are operational.
(b) Flow of biomass From one trophic level to the next is controlled only by the level of the biomass in the succeeding (higher)trophic level
(c) The initial gross outflow/gross inflow ratio is assumed to be 1. The trophic levels are at equilibrium.

Case 1: Increase in trophic level 3
(a) Level of trophic level 3 is increased.
(b) Increase in biomass of tropic level 3 means increased consumption of resource. Flow of biomass from trophic level 2 to trophic level 3 increases.
(c) Increased outflow/inflow ratio reduces causes decrease in biomass of trophic level2.
(d) Reduced biomass of trophic level 2 reduces consumption of resource from trophic level 1, reducing flow of biomass from trophic level 1 to trophic level 2. Higher inflow= outflow rate increases the biomass of trophic level 1 (Hairston et al. 1960, Carpenter et al. 1985).
(e) Biomass of trophic level 2 is still reduced till the point where it is unable to sustain trophic level 2. (Decrease in level progressively decreases inflow while the trophic level 3 drains it without control as there is no bottom up control- no resource competition caused mortality.)
(f) Trophic levels 2 and 3 collapse but Trophic level reaches density limit and stays there.

Case 2: Decrease in trophic level 3
(a) The trophic level 3 is decreased.
(b) Decrease in trophic level 3s decreases rate of flow of biomass from trophic level 2 to trophic level 3.
(c) This causes an increase in the biomass of trophic level 2 requiring an increased rate of flow from trophic level 1.
(d) Since the rate of inflow is less that the rate of outflow of trophic level 3, it is depleted to zero (Extinction of 3rd trophic level)
(e) Increased rate of inflow and zero outflow causes the 2nd trophic level to reach maximum spatial density.
(f) Higher rate of outflow and lower rate of inflow will eventually reduce trophic level one to zero.
(g) This causes trophic level 2 to become extinct.
(h) If the density limit on trophic level 2 is sustainable by trophic level 1, the trophic levels 2&3 do not ego extinct but reach a new equilibrium specified the density limit of trophic level 3 and the rate of flow from trophic level 1 to trophic level 2.

Influence of lower trophic level changes in top-down controlled system.

Increase in trophic level 1 does not affect biomass level of tropic level 2 since trophic level 2's biomass is not dependent on the availability of biomass from tropic level 1.

Similarly, decrease in tropic level 1 does not affect the biomass of trophic level 2 till the minimum prey to predator required ratio is reached. After that, the predative tropic level decrease along with the decrease in the resource trophic level.

Variation in tropic level 2: Increase in trophic level 2 causes increased flow of biomass from trophic level 1 but does not affect trophic level 3. Increase in trophic level 2 and decrease in trophic level 1 causes trophic level 2 to reach maximum density limit.

If trophic level 1 is capable of sustaining the increased drain of biomass to trophic level 2, the system stabilizes. If not, trophic level 1 is depleted leading to complete collapse of the system.

Decrease in trophic level 2 (independent of trophic level 3) reduces biomass flow from trophic level 1 causing the biomass of trophic level 1 to increase, if allowed, to the density limit. Trophic level 3 remains unaffected.

Combined Top down and bottom up control

Most ecosystems are regulated by a combination of both top down and bottom up controls. However, one type of control usually predominates. The ecosystem will therefore show the characteristics of the dominant control but at a relatively slower rate since the dominant control will be offset to a limited extent by the weaker control.

Very rarely, an ecosystem may experience equal top down and bottom up control. This system will be a self regulating system which will restore the equilibrium even if one trophic level is upset.

Discussion:

The model indicates that in a pure bottom up controlled system, the requirement that the size of a trophic level is not affected by the preceding trophic level indicates that the resource trophic level has either or both high fecundity(Includes short life span) effective defense against predation. It also indicates weak or inefficient predation and high prey- predator ratio requirement by the predator.

Another indication is that competition in the higher trophic levels is extremely high (territoriality, etc) with high level of mortality due to competition. The level of mortality due to interference competition should be extremely sensitive to change in the resource trophic level.

In summation, Bottom up control is effective where prey defense mechanisms are effective and/or predation is inefficient.

Corollary:

Change of a top order trophic level in a bottom up dominant ecosystem, will affect only the tropic levels (if any) above it and will affect none below it.

The model indicates that in a ecosystem controlled by top down cascade;

- Predator populations require a very low prey-predator ratio. (since the higher trophic level is not affected by the size of the resource trophic level)
- Availability of prey/resource is high. (Since the interference competition is low in its immediate higher trophic level, predator trophic level)
- Prey populations are sensitive to predator population.
- Interference competition is low in predator trophic level. (As evinced from the lack of any bottom up control)
- Prey have relatively low fecundity, higher lifespan & higher body mass. (Higher fertility, lower lifespan and lower body mass would lower the sensitivity of the resource level to it’s immediate higher trophic level)

Top down control is effective in ecosystems with efficient predation and/or weak prey defenses.

Real ecosystems are probably a composite of the two controls with one control having a greater degree of influence. The ecosystem as a result will display the cascade characteristics of the dominant control system. The influence of the dominant ecosystem will however be negated by the effect of the lesser control system and is inversely proportional to the level of influence of the lesser control system.

This model does not consider adaptation. Adaptation can be included in consideration by allowing for change in inflow/outflow characteristics of the trophic levels with reference to the biomass level. That is, in the considered model, the proportion of increase or decrease of the valves with respect to the increase or decrease of biomass level is fixed. If we are to include the adaptational capabilities of species into consideration, then the ratio of valve opening to the float height will vary.

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Figures

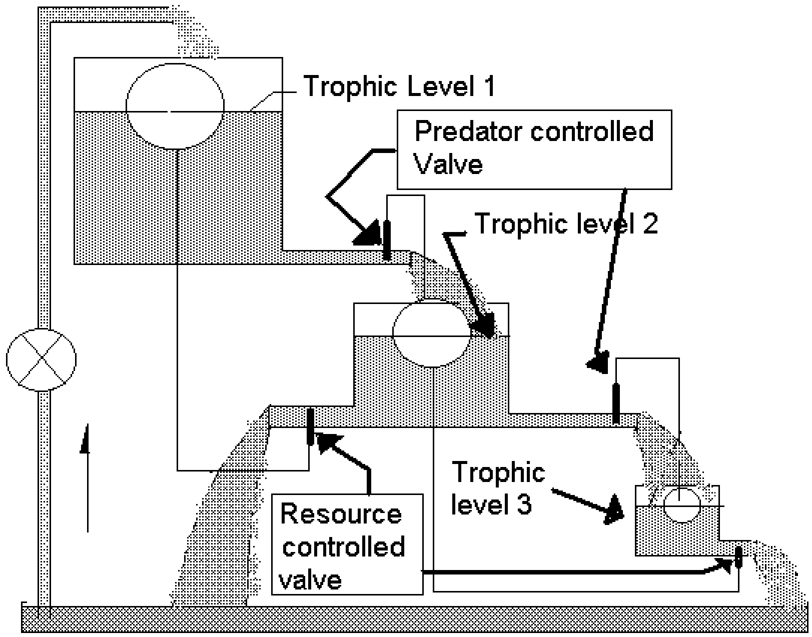

Fig. 1 Basic Model

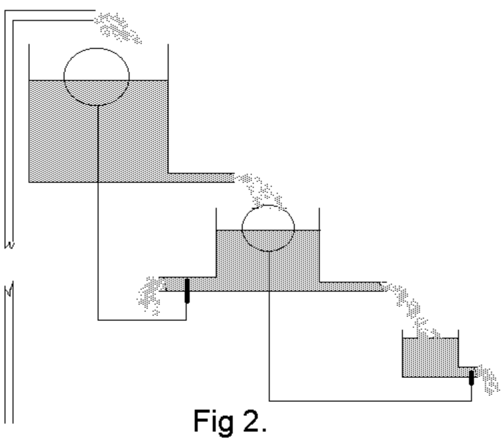

Fig 2.
Pure Bottom-up Control

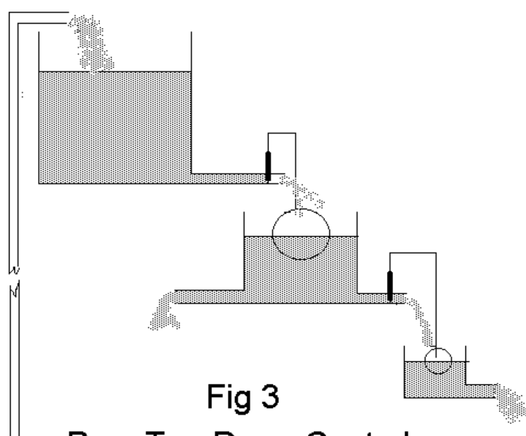

Fig 3
Pure Top-Down Control

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