John Marshall Geography 562 GIS Coastal Resources
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Effects of Oyster Culture on Native Eelgrass and Related Natural Resources in the Puget Sound
A Geographic Information System Based Model

Eelgrass Ecology. In the Pacific Northwest bays and estuaries, eelgrass (*Zostera marina L*.) provides spawning grounds for Pacific herring (*Clupea harengus pallasi*), out-migrating corridors for juvenile salmonids (*Oncorhynchus spp*.) and important feeding and foraging habitats for water birds such as the black brant (*Branta bernicla*) and great blue heron (*Ardea herodias*) (Thom et al 2014). Because of its ecological importance and its rapid response to environmental degradation, eelgrass has been identified as a Vital Sign of ecosystem health, and a 2020 eelgrass recovery target was adopted by the Puget Sound Partnership, which is a public program dedicated to restoring the Puget Sound ecosystem's health (Thom et al 2014).

Burrowing shrimp are native species in our west coast estuaries and can often be found associated with eelgrass populations. They contribute to intertidal and shallow-subtidal ecosystems as important components of estuarine food webs, providing forage for many species of birds, fish, and other shellfish. Their burrows also provide temporary refuge for small fishes and crustaceans, such as gobies, shore crabs, and juvenile Dungeness crabs (WDOE 2017).

Eelgrass Stressors. Aquaculture practices result in tradeoffs with natural systems, but the magnitude of those tradeoffs is strongly dependent on the management practices employed at a given aquaculture operation site. For example, research informs native eelgrass density declines with increases in oyster density on oyster plats (Tallis et al 2009) and mechanically harvested oyster beds contain significantly less native eelgrass than oyster beds harvested by other methods (Dumbauld and McCoy 2015).

Rack and stake oyster culture (primarily introduced *Crassostrea gigas*) can cause reductions in eelgrass density, primarily through shading (USFWS 2009). Stake culture also results in algae increases such as Ulva (sea lettuce) and Enteromorpha. These species compete with eelgrass and are suspected of having an adverse effect on eelgrass survival (USFWS 2009). After disturbance, a reduction in eelgrass density can persist for some time. Oyster culture rack and stake structure eelgrass density reductions have been severe in many areas, in some cases up to 75 percent if stakes and/or racks are positioned too closely to allow adequate light penetration (USFWS 2009). The reduction in eelgrass percent cover and shoot density on oyster plats can persist for over a year or result in eventual complete elimination of eelgrass from oyster plats (USFWS 2009). Fisheries biologist have understood for some time that management actions at the oyster plat level have a range of potential impacts depending on the type of culture, intensity, longevity, and timing of management actions:

> *"Acute disturbances that produce large-scale changes in community dominants, such as manipulation of burrowing shrimp or eelgrass with pesticides or mechanical harvesting and manipulation of oyster grounds, strongly influence the carrying capacity for many fish and macroinvertebrates. Ensuring that estuarine ecosystems are sustainable for the breadth of processes and resources requires a comprehensive assessment of both natural*

and anthropogenic disturbance regimes, landscape influences, and the effects of local management for particular species on other resources (Simenstad and Fresh 1995)".

There remains a certain level of uncertainty about how oyster culture and other stressors affect eelgrass habitat and eelgrass interdependent species. Eelgrass genetic variability likely plays a role in its resilience to stress, but it is not well studied in this region. Research does show it tends to adapt to local conditions. Local adaptation may lower subpopulation genetic diversity while increasing diversity overall in the Puget Sound. This fact makes general assessment of the effects of eelgrass stressors more difficult, because ironically local adaptations may make local eelgrass populations more or less vulnerable to changes in conditions at a given site (Thom and Judd 2011).

In another example of uncertainty, black brant wintering populations feeding almost exclusively on eelgrass in west coast bays and estuaries along the Pacific Flyway have declined significantly along the United States portion of the coastline since the 1960s. But as late as 2002, data were insufficient on the extent and quality of eelgrass habitats at major staging and wintering sites, carrying capacity of primary staging and wintering sites and the effects on brant distribution were poorly known, habitat loss from coastal development and associated disturbances at primary brant staging and wintering sites was not quantified, and the effects of contaminants on eelgrass and brant were unknown (Pacific Flyway Council 2002). Nevertheless, personal communication with U.S. Fish and Wildlife biologists responsible for monitoring coastal waterfowl populations inform it is in their collective opinion that oyster culture operations have likely played a significant role in wintering black brant population declines in west coast estuaries and bays in the United States (Pitkin et al 2000).

Two species of native "burrowing shrimp" [Mud shrimp (*Upogebia spp*) and Ghost shrimp (Neotrypaea spp)] are considered pests by oyster growers because their burrows soften the substrate beneath the introduced commercial oysters and cause them to sink into the mud and perish from lack of oxygen (Griffin 1997). Consequently, there have been extensive efforts by commercial oyster growers to remove these species from their plats (Dumbauld et al 2006), ranging between mechanical removal to highly toxic nontarget pesticide (e.g., neurotoxins such as carbaryl and Imidacloprid) applications (Griffin 1997) (WDOE 2017). At the same time oyster growers have been working to "control" these species, an Asian invasive parasite (Orthione) infestations appear to be driving local Upogebia populations to collapse and near extinction by preventing reproduction (Chapman et al 2011). Upogebia is a critical ecosystem engineer due to its historical abundance and extensive suspension feeding and burrowing activities which influence nutrient flux, benthic community structure and functioning of estuaries (Chapman et al 2011).

Research Problem. Significant portions of intertidal habitat in the Puget Sound are dedicated to oyster aquaculture operations under the premise that they are inherently biologically and ecologically compatible with undisturbed estuarine and marine structure and function. However, history informs us that aquaculture is a type of agriculture that can have serious direct and indirect adverse impacts on native species and the natural habitats they depend on.

Research Question. What are the focal stressors on native eelgrass (*Zostera marina*) and associated native eelgrass dependent species that stem from oyster aquaculture operations in the Puget Sound and what is the ordinal magnitude and geographic distribution of these stressors?

Research Task. This project attempts to isolates one key habitat type, native eelgrass, itemize focal stressors, and use a Geographic Information System (GIS) based model to spatially evaluate the geographic distribution and relative magnitude of these stressors in the Puget Sound area of Washington State.

The GIS Model. It was deemed that the model should be organized to reflect the nature of the research problem and question for it to be able to implement the research task (Figure 1). Since it is a geographic information system based model, the first step was to consider the appropriate geographic extent. The problem statement identifies intertidal habitat in the Puget Sound and the model adopts this area as its extent. It should be noted that while the focal habitat (native

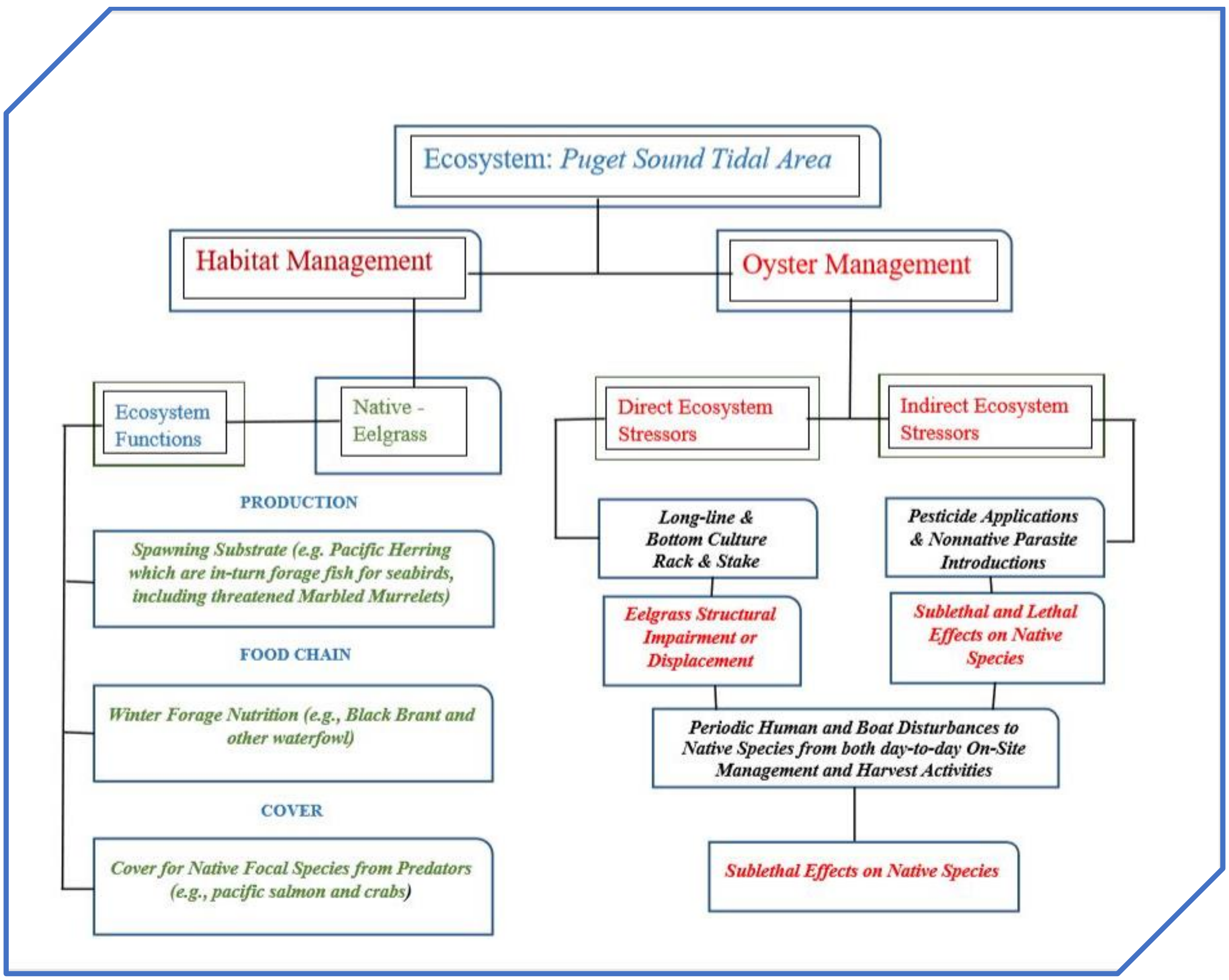

Figure 1. Model Foundation Diagram.

eelgrass) extends to shallow subtidal areas along many Puget Sound bathymetric gradients, the oyster culture plats are only present in the intertidal areas. Since the focus of the problem

Credits

Production	Native eelgrass provides spawning substrate for Pacific Herring.	
Food Chain	Pacific Herring are forage fish for sea birds and marine mammals. Wintering Black Brant feed almost exclusively on eelgrass	**Diatoms**, bacteria, and detritus gathers **on eelgrass** leaves providing **food** for many invertebrates; including some clams.
Cover	Juvenile salmon use eelgrass to avoid predators.	Native crabs use eelgrass to avoid predators.

Debits

Structural Displacement	Oyster bottom culture, longline, and rack and stake can result in mechanical tearing of fragile eelgrass blades eliminating them from an entire plat. The reduction in light from shellfish bed structures can be associated with reduced eelgrass presence.	Oyster bottom culture, longline, and rack and stake can result in prevention of new eelgrass growth over an entire plat. High-density structures may increase sediment deposition, reducing eelgrass growth. Digging and dredging activities immediately reduce eelgrass presence.
Structural Impairment	Oyster bottom culture, longline, and rack and stake can result in mechanical tearing of fragile eelgrass blades decreasing blade density or eliminating it from entire sections of a plat.	Oyster bottom culture, longline, and rack and stake can result in prevention of new eelgrass growth over significant sections of a plat.
Lethal Direct	Pesticides used to control native burrowing shrimp kill these important estuarine species utilizing areas inside oyster plats.	Pesticides used to control burrowing shrimp likely expose and kill other 'non-target' native species (e.g., juvenile salmon and crabs) when they use eelgrass in oyster plats.
Lethal Indirect	Pesticides can persist and drift from the application areas into other estuarine areas indiscriminately killing many organisms in its path.	Nonnative parasites on native burrowing shrimp hosts may be decimating their hosts over large areas in Pacific Northwest estuaries.[i]
Sublethal Direct	Oyster boats transporting growers and growers walking in their plats tending and / or harvesting oysters disturb black brant off their feeding areas diminishing their winter reserves for the spring migration.	Pesticides used to control native burrowing shrimp may impair these important estuarine species utilizing areas inside oyster plats and make them more susceptible to disease and predation.
Sublethal Indirect	Oyster boats and growers travelling to their plats and walking on their plats disturb nearby black brant off their feeding areas diminishing their winter reserves for the spring migration.	Pesticides can persist and drift from the application areas into other estuarine areas indiscriminately impairing numerous organisms in its path, making them more susceptible to other perturbations.

[i] This is highly speculative consequence of oyster culture.

Figure 2. Model Assumptions Supporting Credits and Debits.

addresses oyster culture impacts to native eelgrass, the geographic position of the oyster plats was adopted to delimit the extent of the model.

At the next level, the model acknowledges that the research problem basically wants us to resolve the ordinal impacts and spatial distribution of those impacts on native eelgrass habitat and its associated interdependent species. In other words, at each oyster plat in the model's extent overlapping eelgrass, what are the quantified amounts of native eelgrass carrying capacity and what are the quantified amounts of oyster culture related stressors detracting from those respective carrying capacities? To reflect this dichotomy between focal habitat carrying capacity (aka credit) and stressors (aka debit), the model breaks the analyses into two major management sections: habitat management and oyster management.

CREDITS		DEBITS	
Production:	0 to 500	Structural Displacement:	0 to -300
+		Structural Impairment:	0 to -300
Food Chain:	0 to 500	Lethal Direct:	0 to -250
+		Lethal Indirect	0 to -250
		Sublethal Direct:	0 to -200
Cover:	0 to 500	Sublethal Indirect:	0 to -200

= Total Potential Credit (1500) x Acres | = Total Potential Debit (0 to -1500) x Acres
= Total Potential Credit Value | = Total Potential Debit Value

NET CREDIT: Total Potential Credit Value + Total Potential Debit Value

Pre-Record Net Credit Classification Table

Range	Value
<=500	Low
> 500 and <=750	Moderate Low
> 750 and <=1000	Moderate
>1000 and <=1275	Moderate High
>1275	High

Figure 3. Model Logic

On the habitat management side of the equation, the model focus is on native eelgrass habitat and three selected native eelgrass primary habitat process functions (production, food chain, and cover). On the oyster management side of the equation, the model focus is on direct and indirect oyster culture stressors on native eelgrass and interdependent biota, including structural and nonstructural stressors.

The next step was to drill closer into the model and define and articulate the supporting assumptions (Figure 2) used to defend the primary habitat process function and stressor selections. The model's supporting foundation assumptions were derived both from the relevant literature and through personal experience working with the model's focal resources for over a period of 25-years as a professional resource manager and fish and wildlife biologist.

For ordinal comparisons of the net outcomes of eelgrass carrying capacities remaining on oyster plats post stressor exposure, carrying capacity (credits) and stressor (debits) were created to be employed by the model as a measurable currency (Figure 3). Ideally this exercise would have been done using careful reviews of the management plans (possibly using preconstruction notification plans required by the U.S. Army Corps of Engineers per their authorization of nationwide permit number 48 for aquaculture) of each oyster plat in the model's extent, along with selected site level field verification visits. The currency amounts and ranges could have then been retroactively modified to best reflect the resulting verified field data. But since this was not possible per the limitations of time and resources available for this class project, more or less arbitrary numeric selections and ranges were assigned to the model currency, and then also applied arbitrarily to each oyster plat record, on both the credit and debit side of the equation. This allows the model design theory and logic to be tested but the model outcomes cannot be used at this time to reflect real world representation. It should also be noted that the range categories displayed in Figure 3 are displayed for method illustration purposes only. They do not reflect the actual model derived ranges classified after the debits and credits were weighted by acreage.

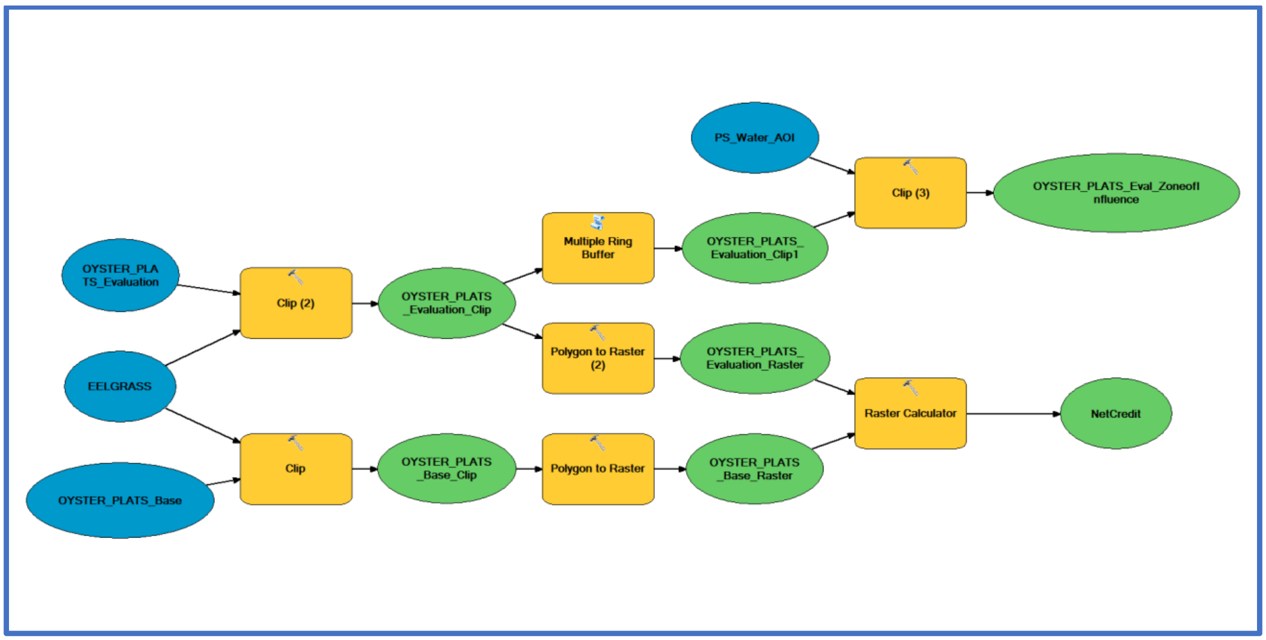

Figure 4. Model Geoprocessing in ArcGIS Model Builder.

Model Application in ArcGIS Model Builder. The first steps in developing the model in ArcGIS Model Builder required two versions of the oyster plat data to be created, a base layer to calculate credits and an evaluation layer to calculate debits. Both datasets were pre-prepared for use in the model by adding them to an ArcMap project and then opening their attribute tables and using the add field function to create the necessary data fields (float data type/scale = 2). The field calculator was used to populate both the field input and calculated field records (Table 1 and 2).

Table 1. Oyster Plat Base (Credit) Layer.

OID	Production	FoodChain	Cover	TotalCredit	Acres	TotalCreditVal
1	400	300	250	950	0.95	902.5
2	500	450	375	1325	44.99	59611.75
3	100	100	75	275	21.46	5901.5

Table 2. Oyster Plat Evaluation (Debit) Layer

OID	StrucDisp	StrucImp	LethDir	LethIndir	SubLethDir	SubLethIndir	TotalDebit	Acres	TotalDebitVal
1	-25	-150	-250	-50	-75	-25	-575	0.95	-546.25
2	-100	-325	-125	-150	-50	-25	-775	44.99	-34867.25
3	0	0	0	0	-25	-25	-50	21.46	-1073

The next step is to clip both above layers to the eelgrass layer to ensure only oyster plats overlapping eelgrass are evaluated. Each of the output clip layers is then converted to a raster with the value focal cells set to TotalCreditVal and TotalDebitVal respectively. The Raster Calculator is then used to sum the two output rasters with an ‘add’ operation I set up as an expression in the Raster Calculator tool (Figure 5). An output raster is then generated displaying the net credits remaining in the georeferenced cells once the cell add operations are completed.

Base Raster + Evaluation Raster = Output Raster

902.5	-546.25	356.25
59611.75	-34867.25	24744.5
5901.5	-1073	4828.5

Figure 5. Oyster Plat Base (Credit) Layer + Oyster Plat Evaluation (Debit) Layer

The net credits raster was added to an ArcMap project and then classified across a stretched high to low net value range. Selected zoomed in views at individual oyster plat extents are then used as example model outputs and exported as pseudo-maps for display and discussion purposes (Figures 6, 8, and 10).

To illustrate potential oyster plat zones of influence on areas in the tidal and subtidal surface waters outside the oyster tract footprints, a multiple ring buffer tool was run on the oyster plat evaluation layer (3 indirect influence distance zones were set at 100-ft, 1000-ft, and 10000-ft) and clipped to the Puget Sound Water Area of Interest polygon. The resulting output polygon was added to the same ArcMap project discussed above and then symbolized. Selected zoomed in extents were exported as pseudo-maps (Figures 7, 9, and 11) for display and discussion purposes.

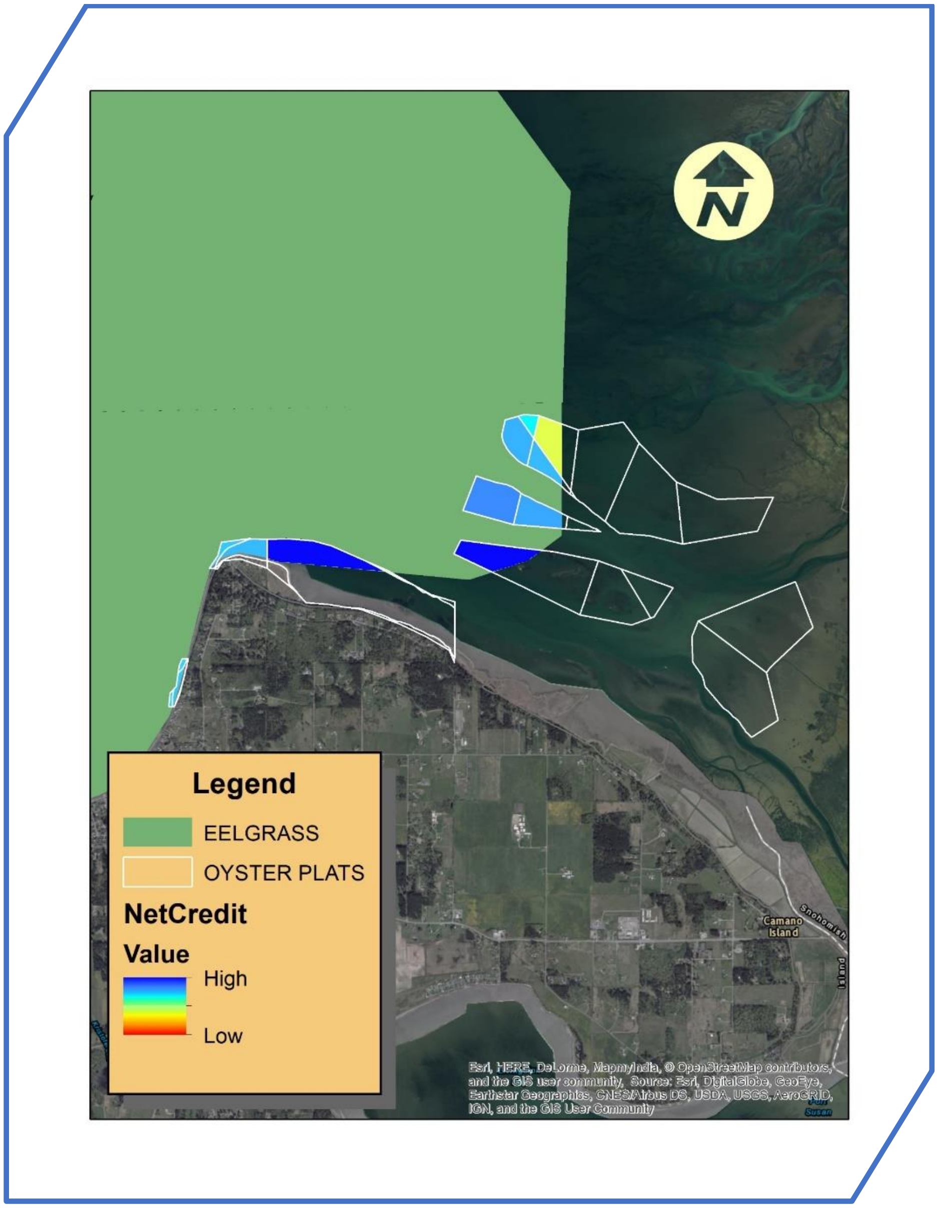

Figure 6. Preliminary Trial Classification Test Site A1.

Trial Classification Test Site A1 in Figure 6 above is used solely to test model operations and logic. Because of the lack of site level data, arbitrary data inputs were used. Therefore, no real-world inferences can be made based on this output.

Figure 7. Preliminary Trial Classification Test Site A2 (Zone of Influence).

Zone of influence distance zones are arbitrary and not based on any documentation. Nor is there any attempt built into the model to assign them a credit or debit value.

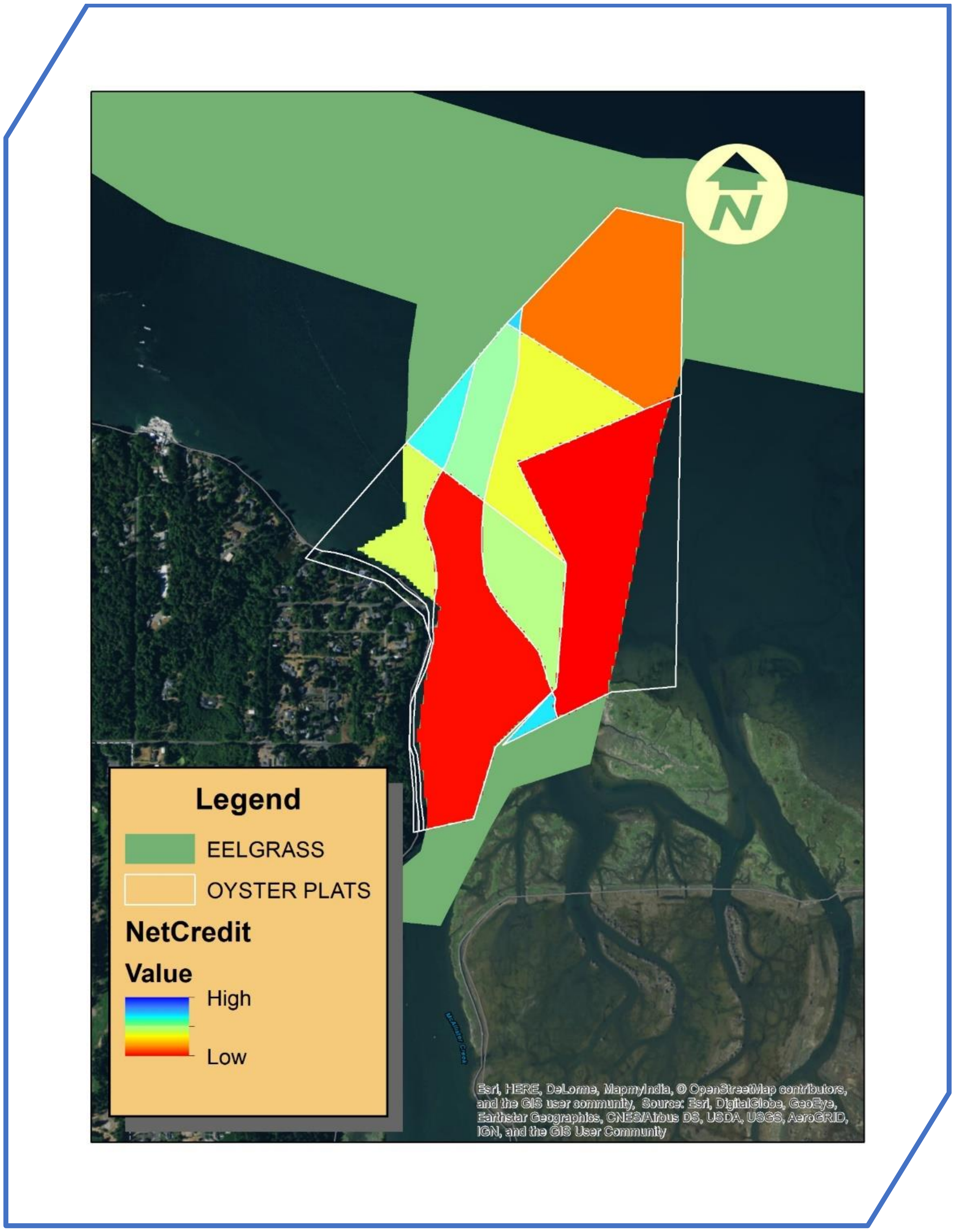

Figure 8. Preliminary Trial Classification Test Site B1.

Trial Classification Test Site B1 in Figure 8 above is used solely to test model operations and logic. Because of the lack of site level data, arbitrary data inputs were used. Therefore, no real-world inferences can be made based on this output.

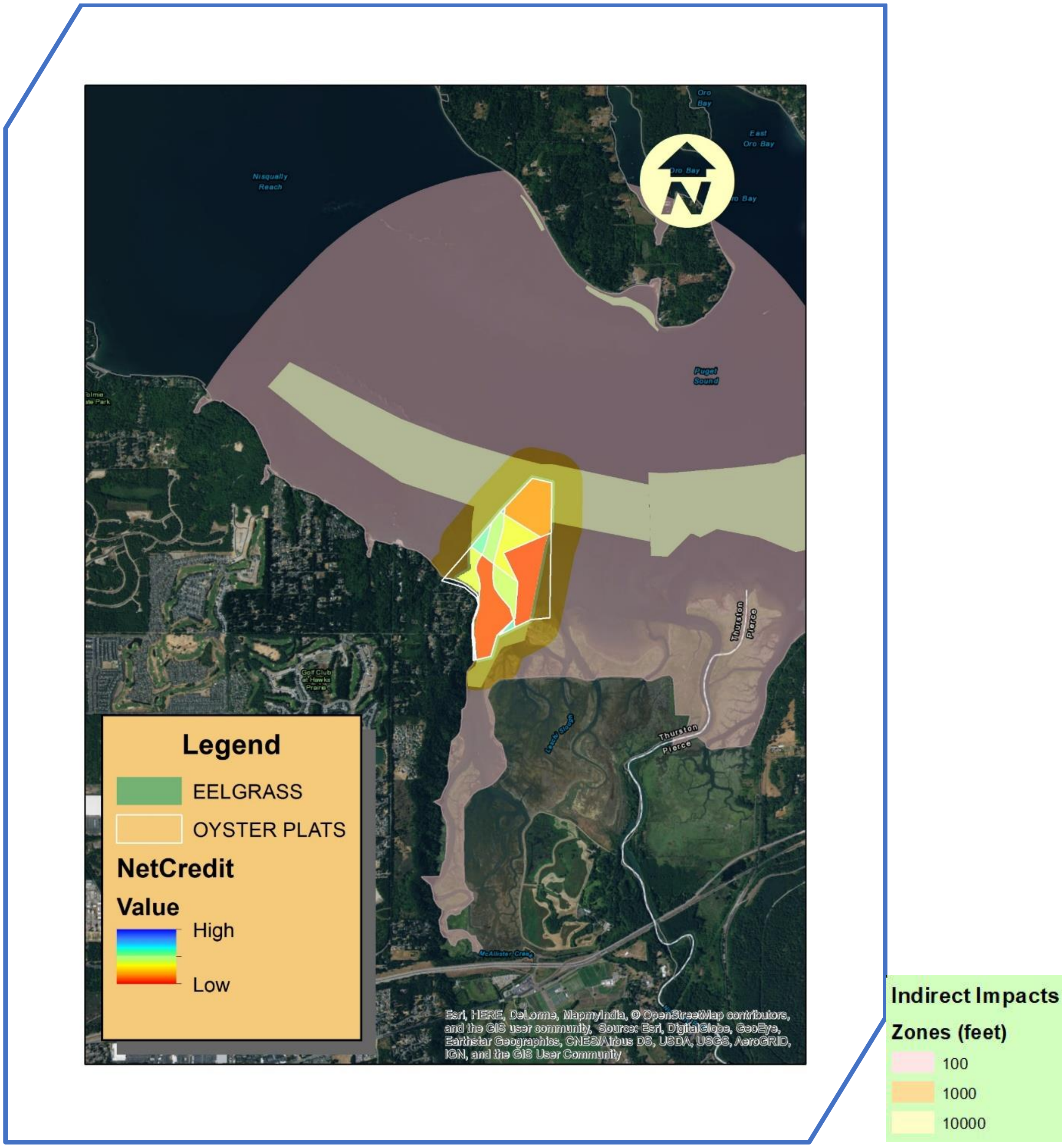

Figure 9. Preliminary Trial Classification Test Site B2 (Zone of Influence).

Zone of influence distance zones are arbitrary and not based on any documentation. Nor is there any attempt built into the model to assign them a credit or debit value.

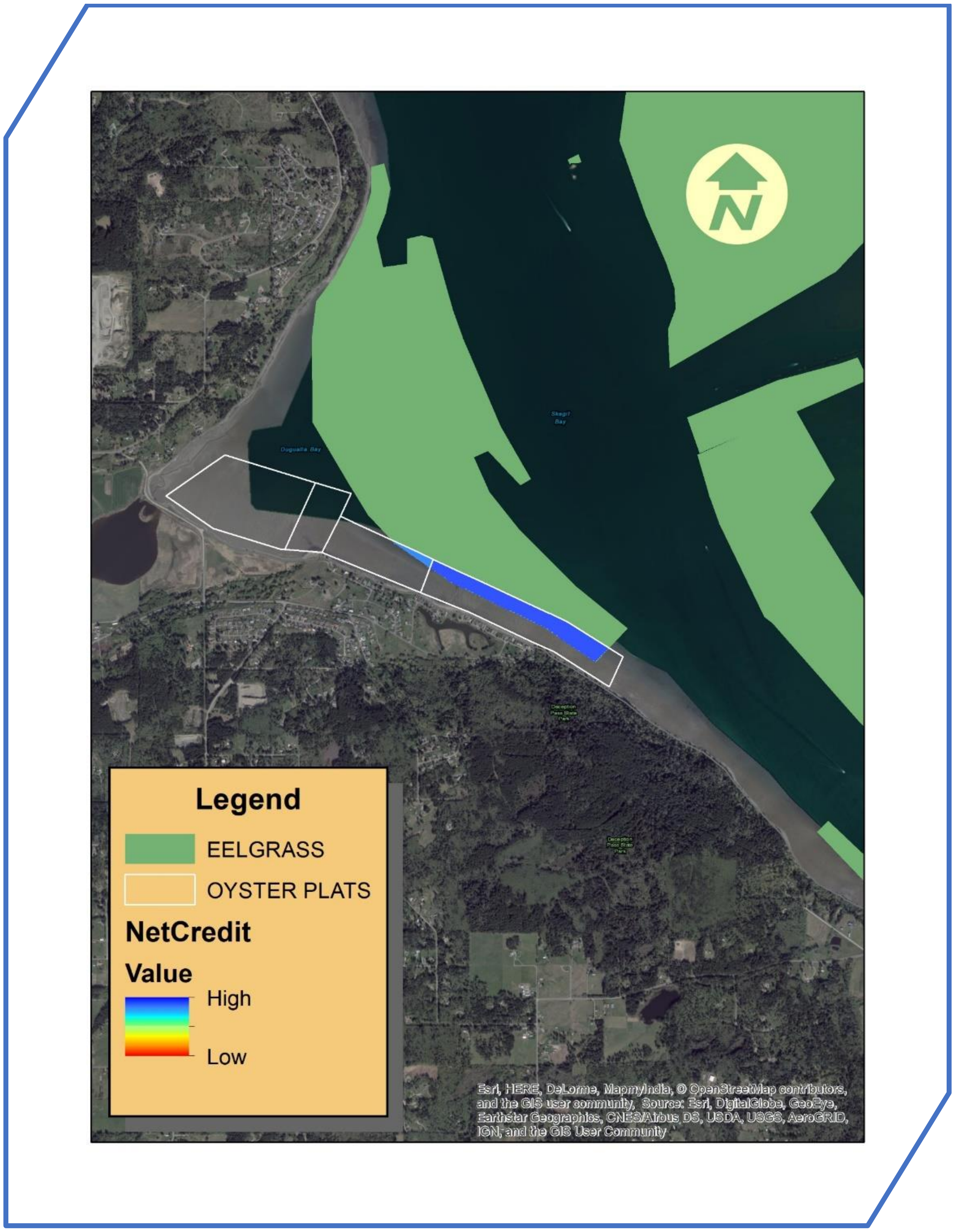

Figure 10. Preliminary Trial Classification Test Site C1.

Trial Classification Test Site C1 in Figure 10 above is used solely to test model operations and logic. Because of the lack of site level data, arbitrary data inputs were used. Therefore, no real-world inferences can be made based on this output.

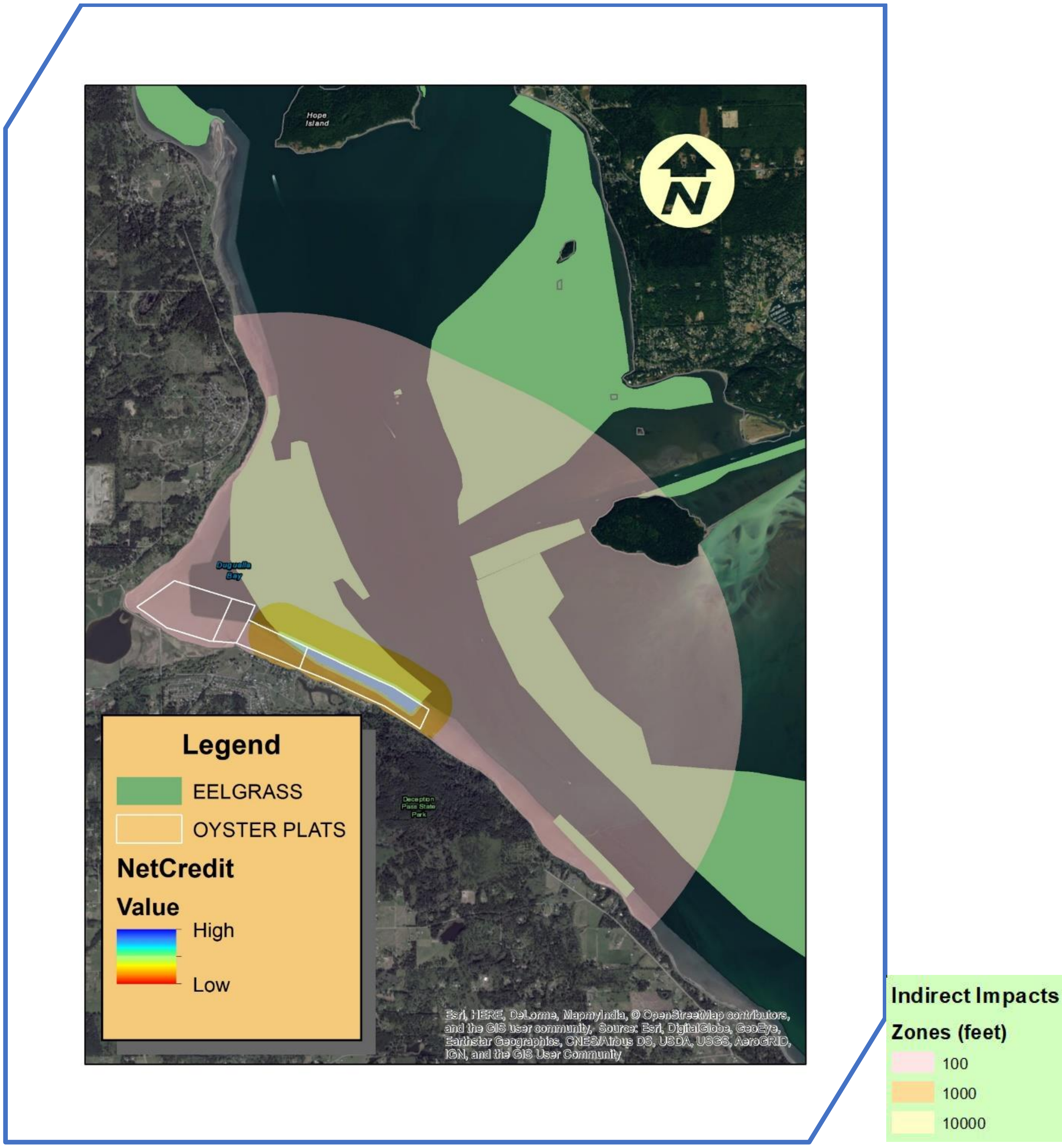

Figure 11. Preliminary Trial Classification Test Site C2 (Zone of Influence).

Zone of influence distance zones are arbitrary and not based on any documentation. Nor is there any attempt built into the model to assign them a credit or debit value.

Model Weaknesses

1. The model base assumptions are coarse and nonspecific about the management practices contributing to perturbation (debit) ranges as well as the ecological foundation for the process and function (credit) ranges.

2. No attempt was made to research specific management plans by oyster plat and individual oyster plat credit and debit values were selected arbitrarily for model test runs.

3. The model does not provide a graphical user interface (GUI) for users to input new data into the model as it becomes available.

4. Model net credit values only addresses areas where native eelgrass and oyster plats overlap.

5. The algorithm used to evaluate the carrying capacity (credit) and oyster plat related perturbations (debit) to subsequently derive the remaining carrying capacity (net credit) is highly simplistic and likely unrepresentative of actual adverse effects of cited perturbations on a specific area's carrying capacity.

6. The model's evaluation focus on areas of eelgrass overlapped by oyster plats does not account for the overall size of the eelgrass patches or their positions and geometric shapes relative to one another and other natural resources.

7. Zone of influence distances are arbitrary and not based on documentation, nor is there any attempt to assign them a credit or debit value.

Figure 12. Model Weaknesses.

Conclusion. Through literature review and personal experience, reasonable lists of eelgrass habitat process functions and oyster culture stressors were compiled. A model structure was designed using carrying capacity as a guiding principle for its conceptual framework and operational logic. However, the lack of standardized on-site data for each of the oyster plats containing eelgrass habitat made model calibration and meaningful data interpretation of real-world circumstances unobtainable at this time. Seven model weaknesses are listed in Figure 12, but they should not be considered exhaustive or in any way a comprehensive representation of all the model's short comings.

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