Marine Policy 91 (2018) 22–33

Contents lists available at ScienceDirect

Marine Policy

journal homepage: www.elsevier.com/locate/marpol

Making better decisions: Utilizing qualitative signed digraphs modeling to enhance aquaculture production technology selection

Andrew S. King[a,*], Nicholas G. Elliott[b], Catriona K. Macleod[c], Mark A. James[d], Jeffrey M. Dambacher[c]

[a] *Institute for Marine and Antarctic Studies, University of Tasmania, Hobart 7000, Australia*
[b] *CSIRO, Castray Esplanade, Hobart, Tasmania, Australia*
[c] *Institute for Marine and Antarctic Studies, University of Tasmania, Hobart, Australia*
[d] *Scottish Oceans Institute, School of Biology, University of St Andrews, East Sands, St Andrews, Fife, KY16 8LB, United Kingdom*

ABSTRACT

Understanding causal relationships within complex business environments represents an essential component in a decision-maker's toolset when evaluating alternative aquaculture production technologies. This article assesses the utility of employing signed digraph qualitative modeling to support technology selection decision-making through evaluating the adoption of three alternative production expansion strategies (offshore production, IMTA, or land-based RAS) by the Atlantic salmon industry. Results underlined the benefits of strategically understanding the dynamics of demand growth, emphasized the requirement to address societal concerns early; and indicated that levels of ambiguity are lowest with expansion offshore and highest with land-based RAS growout. The research suggests that signed digraph modeling can provide an objective perspective on the levels of uncertainty and causal linkages within a business environment when exploring aquaculture adoption technology scenarios.

1. Introduction

The efficacy of adopting emerging alternative production technologies and strategies to expand the aquaculture industry is subject to a multiplicity of interrelated impacts. In particular, as production within a region matures the business environment becomes increasingly complex, and the challenges associated with achieving and maintaining a ‘social-license to operate’ rise [10,3,54]. To better assess, understand and manage within this multifaceted environment the industry would benefit a decision-support approach that can capture, relate and adjust the many conflicting elements associated with societal concerns, technical production requirements and market economics.

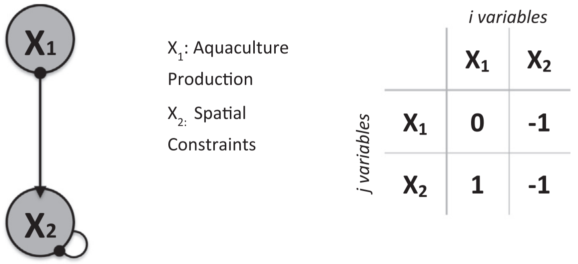
Traditionally modeling efforts to support development and expansion in the global aquaculture industry have relied upon relatively simple comparative modeling using spreadsheets [11,52]. These have been accompanied by economic projections of supply and demand [37,44,50]; the application of geographical information system analysis to identify and scope development potential [30,7]; the numerical simulation of site discharge loadings and site biomass modeling [13,28,49]; and the formulation of top-level strategic plans [13,26,28,49,51]. These approaches, while useful, can only represent isolated snapshots of the system and do not reflect the dynamic interactions or feedbacks operating within the business environment, nor do they take any account of the broader processes / interactions that might occur outside of the production environment. Increasingly there has been recognition of the wish for decision-support techniques and understanding that can better reflect the responses and links between social, economic and technical factors in relation to aquaculture systems [36,48,66], and the regulatory responses from public agencies [54].

Qualitative signed digraph (sign directed graph) models are one way that a holistic overview of a process or industry can be developed [40]. These models are focused on defining the causal relationships (feedbacks and interactions) between variables, and increasing the understanding of current and future dynamics, thereby providing the ability to predict the direction by which a system might change as a result of any perturbation or intervention. Such models can incorporate different components (i.e. governing bodies and markets) and processes (i.e. local customs) that are important in defining the outcome but have traditionally been difficult to incorporate. The sign digraphs are relatively easy to construct and can be used to identify key relationships and processes, highlight data-gaps, distinguish change thresholds,

---

[*] Corresponding author.
E-mail address: andrew.king@utas.edu.au (A.S. King).

https://doi.org/10.1016/j.marpol.2018.01.032
Received 23 November 2017; Received in revised form 28 January 2018; Accepted 30 January 2018



	X_1	X_2
X_1	0	-1
X_2	1	-1

Fig. 1. A stylized example of Signed digraph and 'Community' matrix representations for aquaculture spatial regulation. Positive direct interactions / effects are shown by arrows (or +1 in matrix), and negative direct interactions by lines ending in a circle (or −1). Self-effects are depicted by lines returning to the source variable, which may be either positive or negative. Perturbations (increases) occur down the matrix columns, whilst responses (predictions) to perturbations are read across rows.

assess the systems stability (i.e. the propensity to return to equilibrium) [41,21], and to formulate management strategies aimed at understanding and influencing the 'tipping points' of the system [9].

The technique has been extensively applied in natural resource management, including fisheries [19,42,47,53] and has been used to help address a range of societal challenges [45]. Signed digraph modeling can also be applied to economic [56,59] and investment decisions [46,6]. However, this qualitative modeling technique does not appear to have been applied in aquaculture decision-making, nor have the triumvirate elements of business development (societal, economic and technological) been combined in such modeling.

The purpose of this study is to address this challenge by undertaking an assessment of the applicability of qualitative signed digraph modeling to support aquaculture decision-making. Specifically, through evaluating the selection of alternative growout production technologies by the Atlantic salmon aquaculture industry. An industry where rapid technological change has driven productivity growth and improved management [38,4].

2. Method

2.1. Signed digraphs qualitative modeling

Qualitative signed digraph modeling uses sign-directed graphs to portray the structure of the system to be modeled. Through defining the core variables and their direct relationships the links from one variable to another are depicted in sign-directed graphs by lines ending in either: an arrow (→) to represent a positive direct effect; a filled circle (-•) for a negative direct effect [55,21]; or a square annotated with a +/- for an effect that can be either positive or negative depending on certain conditions. Self-effects are shown as links that start and return to the same source variable, and reflect influences from factors outside of the system, or density dependent growth (for a biological system).

To illustrate through a stylized example (Fig. 1). The process of spatial regulation for (sea-pen) aquaculture can be broadly represented by two variables – Aquaculture Production (X1) and Spatial Constraints (X2), (Fig. 1), with the links and interactions between these variables denoted in matrix format [21].

In this 'Community' matrix, each a_{ij} element represents the direct effect of variable i on variable j (Fig. 1). In the example shown, spatial constraints *(row 2)* can be seen to increase (1) from a perturbation (a sustained external pressure) to aquaculture production *(column 1),* while aquaculture production *(row 1)* is negatively impacted (− 1) by an increase in the spatial constraints *(column 2)*. As production within a region (X_1) increases, the availability of suitable seawater space reduces and thus spatial constraints (X_2) rise ($X_1 \rightarrow X_2$). Correspondingly should spatial constraints increase by say the designation of a marine protected area, this will stimulate a negative direct effect on production (X_2-•X_1), thereby stabilizing aquaculture development within a region to an 'acceptable' level.

To reflect both direct and indirect interactions between variables the Adjoint matrix (a conjugate transpose of the Community matrix) is derived [20]. The direction of change (increase or decrease) of all the systems variables after a sustained change (perturbation) is given by the signs of the Adjoint matrix coefficients (Fig. 2). When negative, a feedback cycle returns the opposite effect to an initial change to a variable and acts to maintain equilibrium, whilst positive feedback keeps displacing a variable away from its original value, increasing a system's sensitivity to a sustained change (a perturbation).

The net number of effects detailed in the Adjoint matrix can also be used to assess the relative magnitude of a predicted response, and the feedbacks and dynamics of the model (the mix of positive and negative cycles at each level) can be examined to determine how the system responds to perturbations (sustained changes). This can help decision-makers better understand the complexities of the system behavior, providing insights into questions such as: what is the impact or direction of change for any component variable given a specific perturbation; and, does the perturbation(s) affect all system variables, or only a few?

Predicting the overall effect of a change (perturbation) to system variables requires the total number of positive and negative effects (both direct and indirect) to be accounted for [21]. If all effects are of the same sign then there will be absolute sign determinacy in a model's

	Aq (1)	Fi (2)	Imp (3)	Sp Con (4)
Aq (1)	0	0	0	-1
Fi (2)	0	-1	0	0
Imp (3)	0	0	-1	0
Sp Con (4)	1	0	0	-1

Community Matrix

	Aq (1)	Fi (2)	Imp (3)	Sp Con (4)
Aq (1)	10	-5	-5	-10
Fi (2)	-5	41	-14	5
Imp (3)	0	-11	44	0
Sp Con (4)	25	-7	-7	30

Adjoint Matrix

Key: Aq (1) Salmon aquaculture production, Fi (2) Commercial salmon fisheries production
Imp (3) Imports of salmon, Sp Con (4) Marine spatial constraints to sea-pen production

Fig. 2. Community and Adjoint matrix representations of four variables within a 14 variable system (depicted in Appendix A). The Community matrix identifies the direct interactions between the variables. The Adjoint matrix shows the direction of change (increase or decrease) and the net number of effects (direct and indirect) that contribute to a variable's response.