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Chapter 12

ARE ECOSYSTEM MODELS AN IMPROVEMENT ON SINGLE-SPECIES MODELS FOR FISHERIES MANAGEMENT? THE CASE OF UPPER GULF OF CALIFORNIA, MEXICO

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ABSTRACT

We review the recent applications of ecosystem models (EMs) as tools for fisheries management in the Upper Gulf of California (UGC), Mexico. EMs are compared with single-species model applications in the UGC, as a basis for assessing the benefits of each ecosystem model as a tool for evaluating management alternatives capable of diminishing impacts on marine ecosystems. The strengths and weaknesses of different types of EMs and their ability to evaluate the systemic mechanisms underlying observed shifts in resource production are also examined with respect to Ecosystem-Based Fisheries Management (EBFM) general goals. Findings showed that ecosystem modeling has increasingly resulted in support for EBFM in the UGC. However, outputs also proved evidence on that EMs are facing a most complicated situation than single-species models regarding the lack of data. Thus, the step from single-species models to EMs is a stage of the management of the area that does not require the elimination of the first approach, but rather the use of both approaches in a complimentary manner. The challenge is the integration of current ecosystem information to detect the gaps in the collective

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knowledge on the UGC. Insights from this study are valuable in defining a planning model scheme that supports ecosystem-based management policies in local fisheries.

Keywords: Ecosystem model, Single-species model, Upper Gulf of California.

INTRODUCTION

Ecosystem-Based Fisheries Management (EBFM) is a relatively recent concept that has been promoted by international resource management agreements to sustain healthy marine ecosystems and the fisheries that they support (e.g., Law of the Sea Convention, Code of Conduct for Responsible Fisheries). By reversing the order of management priorities (i.e., starting with the ecosystem rather than the target species), EBFM represents a holistic approach and emphasizes an understanding of the reciprocal and complex interactions between humans and marine resources [1]. Ecosystem models (EMs) are tools used within this overall framework to evaluate ecosystem properties and provide practical information on the potential effects of changes in EBFM practices on the ecosystems [2]. A large number of ecosystem models have been designed in recent decades with the goal of best representing the basic features of an ecosystem, given a limited number of data sources [3,4]. Currently, a standard procedure in fisheries management includes fitting an ecosystem model to data and then describing the impacts of fishing pressure and environmental variability on populations and ecosystems [5].

In general, updating fisheries management in developing countries like Mexico from single-species population models to ecosystem models has been gradual. The main modeling efforts continue to be localized to specific areas, such as the Upper Gulf of California (UGC), which is one of the most diverse marine ecosystems on Earth [9] and one of the best studied in Mexico [7]. Extreme climatic conditions, along with a lack of a connection to the open ocean, have led to particular physical characteristics in the UGC, such as ample tide intervals (10 m), shallow areas and extreme temperature ranges (8 - 30 ºC), as well as elevated turbidity, evaporation and salinity indices [8]. These attributes are favorable for several species, which promotes a highly diverse ecosystem. Unfortunately, the biodiversity of the UGC has deteriorated due to human activities related to the diversion of water from the Colorado River for irrigation and municipal uses and due to the increase of artisanal and industrial fishing activities [9]. With the aim of preserving the biodiversity of the area while also planning for the development of fisheries, management strategies have commonly focused on single-species regulations, such as seasonal and spatial closures, minimum size limits, fishing effort controls, and quotas. Currently, conservation efforts have being implemented to repair the damage done to the marine ecosystems. The most significant effort occurred when the Upper Gulf of California and the Colorado River Delta Biosphere Reserve (UGCandCRDBR) was established in 1993, and the most recent effort occurred when the refuge area of Mexico's only endemic marine mammal, the vaquita (*Phocoena sinus*), was established in 2005 [10].

However, the application of fisheries policies in the UGC has not been effective in the recovery of fish or other protected species [11], and even in recent years, the pressure on fisheries resources, such as shrimp, fish and elasmobranchs, has increased dramatically [12]. For several reasons (e.g., insufficient involvement of local communities in management, conservation, and enforcement measures), the success of both single-species and ecosystem-based regulations have been limited, but, according to Morales-Zárate et al. [13], one of the most crucial reasons is a lack of an understanding of ecosystem processes.

Because adaptive planning should proactively anticipate the need to change management practices, learn from experience, and adopt strategies accordingly [14], we carried out a literature review on the current state-of-the-art assessments of this type in the UGC. Ecosystem models were compared with single-species model applications in the UGC, as a basis for assessing the benefits of each ecosystem model as a tool for evaluating management alternatives that are capable of diminishing fishing impacts on marine ecosystems. Although EBFM continues to evolve with a broad discussion of definitions and interpretations of concepts, methods, and scopes [15], there are basic principles that are commonly expressed in the literature such as society participation, the balance of conservation and use, integrated management, spatio-temporal scales, and ecosystem dynamics [16]. Thus, this study discusses results with respect to general goals of EBFM that are directly involved with the main contributions of the ecosystem models, such as ecosystem dynamics and spatio-temporal scales, as well as goals addressing the search for a balance between conservation and use. We think that insights from this study are valuable in defining a planning model scheme that supports ecosystem-based management policies in local fisheries.

ECOSYSTEM MODELING

Starfiel et al. [17] described a model as a purposeful representation of a system that consists of a reduced number of system elements, the internal relationships between these elements, and the relationships between system elements and the surrounding environment of the system. In fisheries science, the first models were single-species population models. These were required to make predictions about the direct responses of target populations and the incidental mortality of other biota for evaluating alternative management choices [18]. However, these models did not provide measurements of indirect effects of the use of a target resource on other biota and the whole ecosystem. Ecosystem models were thus designed to provide information on how ecosystems are likely to respond to changes in management practices involving ecological processes, environmental variables, and social-ecological relationships [2].

However, there is not yet a global consensus on how ecosystem models may be directly used within a standard framework for decision-making in EBFM [19]. EBFM is still being developed in a resource management framework [15] and not only requires an understanding of the system, but must also deal with high levels of uncertainty, divergent interests of stakeholders, and, often, a great urgency for decision-making [20]. Furthermore, the difficulties of constructing, parameterizing, calibrating, and validating ecosystem models complicate their approbation [21]. Contrary to stock assessment models, which have provided robust biological reference points for setting control mechanisms (e.g., spawning-stock biomass, maximum sustainable yield) [18], ecosystem modeling has no methodological benchmarks against which one may evaluate these models [2]. As a result of these unresolved challenges, the structural assumptions of these models are usually not considered, and their reliability is poorly understood [22]. Consequently, the value of ecosystem models may generally be over-estimated in the decision-making process, with the danger of giving more credibility to the outputs of these models than they may warrant [23].

The formal separation of EMs is not always easy, and there are many ways to categorize these models [2,4]. Plagányi [24] designed four categories according to criteria from EBFM, especially in regards to the level of complexity: Extensions of Single-Species Assessment Models (e.g., [25,26]), Dynamic Multi-Species Models (e.g., MSVPA [27]; IBM [3]; MULTSPEC [28]), Dynamic System Models (e.g., OSMOSE [29]; ATLANTIS [30,31]), and Whole Ecosystems Models (e.g., Ecopath with Ecosim [2,32]; Loop Analysis [33,34]).

METHODS

To describe the current state-of-the-art approaches in the UGC, single-species and ecosystem models were identified through an electronic bibliographic search within international web searches, Mexican websites, and libraries. The ecosystems models were evaluated in this study with regard to their compliance with the three EBFM goals: (1) understanding the key processes of ecosystem dynamics, (2) using the spatio-temporal scales that are adequate for management, and (3) allowing for a balance between resource conservation and use (Table 1).

Table 1 General goals of ecosystem-based fisheries management (EBFM) directly involved with ecosystem modeling, according to Espinoza-Tenorio et al. [16]

Category	Description
Ecosystem dynamics	EBFM requires the understanding of key processes and relationships controlling the ecosystem. The consideration of ecological and environmental variables and their interdependencies allows us to describe and model ecosystem responses to internal or external perturbations. This understanding enables us to conserve ecosystem structure and function in order to maintain the evolutionary potential of species and ecosystems. EBFM should also examine how perturbations affect distant ecosystem interconnections
Spatio-temporal scales	EBFM should be undertaken at appropriate resolutions to suitably represent ecosystem processes that operate on different temporal scales and affect different spatial extents. For those processes with unclear boundaries (e.g., migration and water currents), it is critical to consider the drivers of change operating both between geographic scales, as well as those occurring over long term periods
The balance of conservation and use	The ecosystem approach should seek an appropriate balance between conservation and use, where the priority is to obtain and maintain long-term socioeconomic benefits without compromising the ecosystem. To achieve this balance, EBFM recognizes that change is inevitable, and therefore, it must be adaptive in its development over time as circumstances change or as new information becomes available. The ecosystems may be managed within the limits of their functioning and

some level of precaution is inevitably required, especially for impacts that are potentially irreversible over long time periods

RESULTS

To represent the fishing dynamics of the UGC, a range of single-species models, from rather simple models limited to commercial fisheries resources such as shrimp [35] and elasmobranchs [36,37], to those which add different species, such as the endemic totoaba (*Totoaba macdonaldi* [38,39]), were used. These single-species models have focused on providing advice on the robustness of management procedures in the UGC. For instance, García-Juárez et al. [35] developed a dynamic model of potential catch quotas for blue shrimp (*Litopenaeus stylirostris*) in the buffer zone of the Biosphere Reserve to estimate the expected shrimp yield and future biomass, including fishing season as a factor and CPUE as an abundance index. This assessment projected levels of biomass under three catch quota management scenarios, recommending the adoption of quotas of 2200 t, which could be increased in some exceptions to 2400 t. A constant harvest rate of 59% of the available annual biomass was also recommended for the management of this resource in the protected area.

In the UGC, most of the single-species models come from official research, which provided technical and scientific advice to the fisheries sector [40]. In this sense, the national institute of fisheries research (INAPESCA, by its Spanish acronym) has based its management decisions on commercial fisheries through indirect assessments, which estimate the parameters of pre-determined selectivity curves simultaneously across mesh size and size class from catch data [41]Kirkwood, G.P. and Walker, T.I., 1986. , Gill net selectivities for gummy shark, Mustelus antarcticus Günther, taken in south-eastern Australian waters. Aust. J. Mar. Freshw. Res. 37, pp. 689–697 Full Text via CrossRef or represent the rate of harvesting through the catch-per-unit effort (CPUE, [42]).

Other contributions of single-species models have been oriented toward conducting historical reconstructions of the stocks to establish crucial parameters and relationships and to describe the current stock status (assessment). Smith et al. [37], for example, determined that, given decades of largely unrestricted exploitation of elasmobranchs in east coast of Baja California, population declines and shifts in size structure are likely to have occurred among those species with the lowest fecundities and latest ages at maturity.

Table 2. Ecosystems models in the Upper Gulf of California according to the arrangement suggested by Plagányi (2007)

Category	Description	Model and local references

Extensions of Single-Species Assessment Models	**Models that expand on current single-species assessments, including only a few additional aspects such as the consideration of species related to target resources or fishing effort**	**[43-47]**
Whole Ecosystems Models	**This category includes approaches that attempt to take into account all trophic levels in the ecosystem to examine the energy flow among components. Models often contain up to 30 species/groups and may include additional socioeconomic variables**	**- Ecopath with Ecosim [13,48-50] - Loop Analysis [51]**

ECOSYSTEM MODELING IN THE UGC

In order to represent the ecosystems in the UGC, two types of ecosystem modeling exercises were performed, as shown in Table 2. These ecosystem models are discussed (below) in regards to their main local contributions to ecosystem dynamics, spatio-temporal scales, and the search for a balance between conservation and use.

ECOSYSTEM DYNAMICS

With respect to the understanding of the key process controlling the ecosystems in the UGC, only in recent decades has the number of models that combine environmental and ecological factors in the UGC increased. The majority of environmental disturbance studies have evaluated the consequences of the drastic reduction in fresh water flow by US dams from the Colorado River. In this sense, the use of extended Single-Species Models has provided evidence for a negative correlation between shrimp catch and discharge from the Colorado River [43]. To investigate the causes of the totoaba fishery collapse, previous studies have analyzed trends in catch, abundance, and fishing mortality in relation to the flow of the Colorado River and a diversity of climatic indexes (e.g. Pacific Decadal Oscillation Index–PDOI) and have reconstructed fishing effort time series [46]. Their results have confirmed the importance of the cessation of the flow from the Colorado River on the catch decrease and have revealed a new strong correlation between catch / abundance and large temporal and spatial scale processes, as shown by the PDOI.

The whole ecosystem dynamic has been addressed by the application of Whole Ecosystem models. For example, Morales-Zárate et al. [13] showed that the UGC is highly dynamic, more complex, and probably a more mature ecosystem than other similar marine systems around Mexico. Using 50 functional groups to represent the UGC, Lozano [49] used mass-balanced models (EwE) to show that this ecosystem is highly dependent on lower trophic levels, mainly detritus-benthic components, which appear to largely control biomasses. Other subsequent whole ecosystem approaches have identified key species when analyzing the function of the system. For instance, Espinoza-Tenorio et al. [51] suggested that fishes, such as milk fish (*Micropogonias megalops*), bass (*Cynoscion othonopterus*), and mackerel (*Scomberomorus concolor*) should be considered as key species when designing management strategies because these species function as buffer species that reduce the direct effects of disturbance on higher trophic levels.

SPATIO-TEMPORAL SCALES

In general, spatial and temporal variations are usually considered separately in ecosystem models. Temporal dynamics are robustly incorporated into all categories of ecosystem models, only distinguishing among those that consider time in a continuous manner from those with discrete time steps that define abstract or physical periods (mostly years, but also hours or decades). For instance, to evaluate the probability of recovery of the endemic vaquita, the implementation of a net phase-out in 5, 10, and 15 years was considered in an Extension of a Single-Species Model [44].

Although limited by the lack of temporal series of information, Whole Ecosystem models also used (temporal periods) time series to simulate fisheries management scenarios. Lercari [50] for example, used ECOSIM (EwE) simulations to suggest that a reduction of 65% in the industrial shrimp fleet, a value similar to the governmental recommendation (50%, [52]), is required within the next 20 years to achieve sustainability of the fishery.

In contrast, the objective of other EwE exercises was to reconstruct the past UGC ecosystem conditions for two periods of time, 1900 and 1990-2002, and thus evaluate the environmental consequences associated with drastic and historical disturbances [49].

While Extensions of Single-Species models do not consider space, the use of EwE and its spatial module, Ecospace, allowed studying the distribution of biological groups and the ecosystem effects of the marine protected areas implemented in the region [48]. This ability of EwE to represent spatial variability is shared with methodological arrangements, such as Loop Analysis-Geographic Information Systems [51], which indentified how fisheries resources (crustaceans, mollusks, fishes, and protected species), as well as the complexity of the trophic nets in which they are embedded, vary across four types of fishing seascapes (Figure 1).

THE BALANCE OF CONSERVATION AND USE

In the UGC, there have not been any practical instances where an ecosystem model was applied at the level of a whole fisheries management plan.

Nevertheless, Extensions of Single-Species models seem to facilitate the search for a balance between conservation and use. For instance, the fishery tendency analysis developed by Rodríguez-Quiroz et al. [47] has successfully shown that the Biosphere Reserve and the recently declared Vaquita Refuge area are important grounds for artisanal fishing. Consequently, they also explained that shrimp capture in both protected areas has maintained a continuous level of production with economic incentives, making it attractive to fishermen, despite recent restrictions on their activities.

Another example oriented toward understanding the conservation and use relationship in the UGC is the shrimp fishing fleet behavior analysis developed by Cabrera and González

[45], which has been presented to the fishing co-operatives as an approach to address social concerns with respect to the technical efficiency of the vessels and co-operatives.

The most realistic representations of Whole Ecosystem models have been generally restricted to specific management strategies.

In these cases, particular interest has focused on the ecosystem's response to specific impacts, such as discards and by-catch. For instance, Morales-Zárate et al. [13] found that most functional groups (29) are impacted more by predation and competition than by fishing pressure in the UGC. Using a pyramid apex angle as an index of ecosystem structure [32], they also showed that use of the ecosystem is balanced. Subsequent Whole Ecosystem models have also been focused on resource exploitation and biodiversity conservation [50,51].

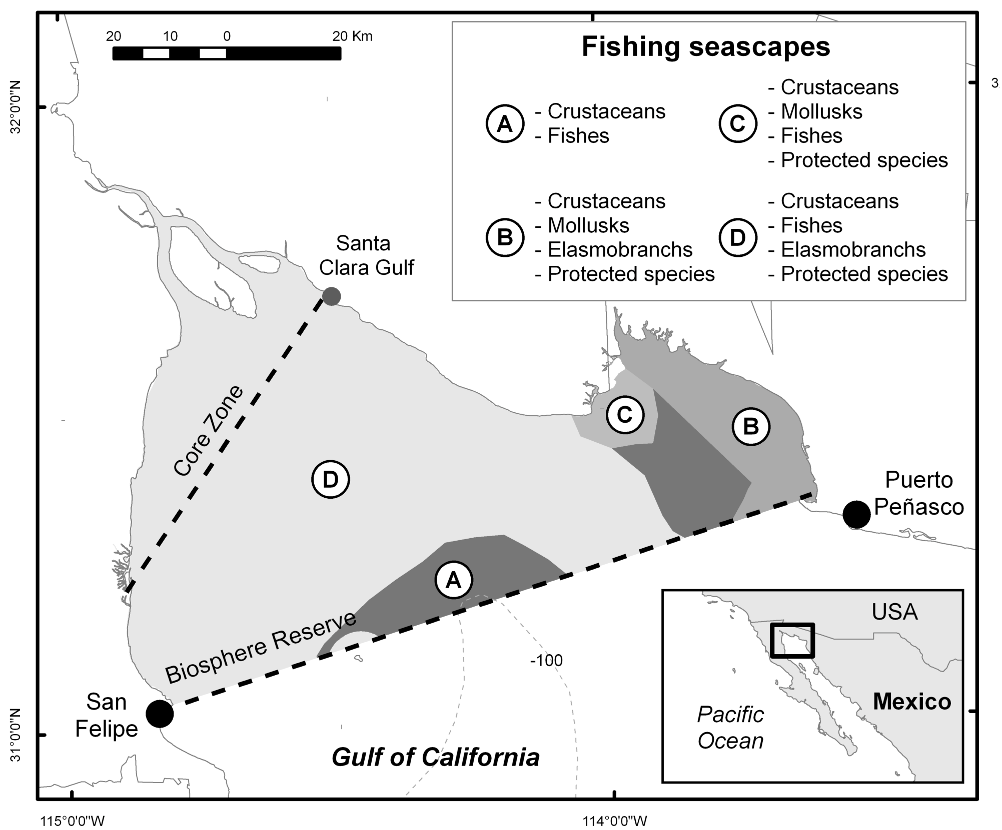

Figure 1. Upper Gulf of California regionalization according to the methodological modeling arrangement Loop Analysis-Geographic Information Systems (modified from [51]).

Discussion and Research Directions

In the absence of long-term monitoring and complex biological data for fishery stock assessment, modeling of the UGC has been oriented toward the establishment of the maximum and minimum catch rates and the understanding of selectivity properties of fishing gear, providing a basis for the implementation of standard mesh-sizes as a regulatory tool for fishery management. Thus, most of these single-species models have proposed specific actions (e.g., total allowable catch) that steer the stock toward a desired status (short-term forecasting); however, few studies have make long-term predictions of the likely future status of stocks under various management scenarios to reach desirable levels (long-term forecasting) [40].

In this context, ecological models are geared primarily toward the three major ecological processes that underlie the forces governing populations: competition, predation, and environmental disturbance. In this sense, Extensions of Single-Species models, which have mainly been restricted to catch data and specific ecological relationships such as predation, have been more recently oriented to specific environmental disturbances, such as the cessation of flow from the Colorado River [43]. The outputs from these models have been used in subsequent, more complex, models to improve, for example, the quality of biomass and productivity information. Whole Ecosystem models have thus addressed competition, predation, and environmental disturbance processes in a more general way, mainly through quantitative and qualitative trophic structure approaches. An approach that has not yet been explored in the UGC is to investigate the hypotheses that have emerged from previous Whole Ecosystem models. In this sense, Extensions of Single-Species models can be used to refine estimates from more complex models on key ecosystem aspects, such as if the biological community is impacted more by depredation and competition than by fishing pressure [13].

Spatial and temporal variations have different grades of advancement in the UGC. The lack of large time series of fisheries information has limited the development of single-species models, now restricted to the ecosystem assessments. However, temporal simulations from Extensions of Single-Species Models and Whole Ecosystem models have evaluated management scenarios, which typically range between a half a year to 20 years in length. Although better computing capacity has recently allowed for spatial modeling, the use of spatial models continues to be limited because of the necessity to represent spatial variability, increased uncertainty, and large data demands, which few approaches are capable of handling. The ability to represent spatial variability is present in Whole Ecosystems models, which face local restrictions because of the lack of georeferenced databases. To overcome such limitations, Extensions of Single-Species Models might explore the spatial strategies that are currently being proposed for the UGC by conservation strategies, such as the refuge area of the vaquita [10], or by Whole Ecosystems models, such as the ecological function of particular fishing seascapes of high biodiversity, like Bahía Aldair [51]. Single-species approaches, such as the dynamic model, which was already proved by García-Juárez et al. [35] for the Biosphere Reserve, can also be useful for analyzing spatial processes.

Due to the presence of both commercially important species and highly endangered species, a balance between conservation and use is a priority for the UGC. However, there have not been any practical instances in which an EM has been applied at the level of a whole-fisheries management plan. This is understandable because finding a balance between conservation and use creates further uncertainty [20] whereby researchers frequently underestimate precautionary limits and managers often do not consider uncertainty [24]. In contrast to the conceptual and abstract index used in Whole Ecosystem models, Extensions of Single-Species Models in the UGC seem to facilitate such a balance due to their capacity to provide estimates of recognized target reference points, such as fishing mortality rates or the risk of extinction [44]. Therefore, both types of models can be used complementarily to facilitate a balance between conservation and use. For instance, Lercari's and Arreguín-

Sánchez's [50] EwE model resulted in effort allocation consistent with those proposed by single-species population models [35] and a decrease in the industrial shrimp and gillnet fishing fleets and an increase in the artisanal shrimp fishery.

Like the search for a balance between conservation and use, society participation and integrated management are two EBFM goals that are not directly involved with the understanding of the system, but lead to the incorporation of social aspects into EMs. Worldwide, these three goals are the least attended by ecosystem modeling [16] because these goals are part of a societal process involving high levels of uncertainty, which is generally avoided by ecological modelers. Although the UGC is no exception to this tendency, some Whole Ecosystem models have been used (e.g., [49,51]), facilitating the involvement of the users through the use of their particular ecological knowledge about fisheries dynamics in the process of building these models. In addition, simple models, such as Extensions of Single-Species Approaches (e.g., [45,47]), seem to be the most promising approaches because they facilitate the participation of the fishery sector due to their simplicity and lower data requirements.

In the UGC, neither Dynamic Multi-Species Models nor Dynamic System Models have been applied. For more detailed studies that combine environmental and ecological factors (e.g., environmental effects of the Colorado River flow cessation), dynamic system models can be useful because they involve both induced changes by environmental disturbances [5] and the effects of ecological driving forces, such as competition and predation [29-31]. Moreover, although Dynamic Multi-Species Models often do not incorporate environmental forcing [4] and usually ignore any potential effects of changing prey populations on the predators themselves [24]. They do provide complete ecological representations of species or groups at higher trophic levels such as vaquita and totoaba in the UGC. However, to implement Dynamic Multi-Species Models or Dynamic System Models, more ecosystem information that is not currently available to the UGC is necessary.

CONCLUSIONS

Ecosystem modeling has increasingly resulted in support for EBFM in the UGC. Thus, the current state-of-the-art of ecosystem modeling approaches in the UGC is beginning to form the whole picture of the ecosystem. However, if single-species models are limited by lack of data used to assess performance of the UGC, the situation with ecosystem models seems to be more complicated because it deals with a high level of uncertainty. The step from single-species models to EMs is a stage of the management of the area that does not require the elimination of the first approach, but rather the use of both approaches in a complimentary manner. If the next stage in the UGC is to explore hypotheses that have emerged from the previous models, it will be necessary to promote the integration of current ecosystem information to detect the gaps in the collective knowledge. Because the dynamics of most of the Mexican marine ecosystems have, in the best cases, only been modeled once, the UGC is an exceptional study area. Lessons learned in UGC should be considered when designing model-structured strategies in other marine ecosystems.

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