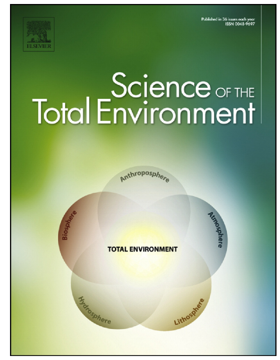

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ABSTRACT

Shaping social-ecological systems towards sustainable, desirable and equitable futures is often hampered by complex human-natural feedbacks, emergence and nonlinearities. Consequently, the future of systems vulnerable to collapse is uncertain under plausible trajectories of environmental change, socioeconomic development and decision-making. We develop a modelling approach that incorporates driver interactions and feedbacks to operationalise future "safe and just operating spaces" for sustainable development. Monte Carlo simulations of fish catch from India's Chilika lagoon are compared to conditions that are ecologically and socioeconomically desirable as per today's norms. Akin to a satellite-navigation system, the model identifies multidimensional pathways giving at least a 75% chance of achieving the desirable future, while simultaneously diverting the system away from undesirable pathways. Critically for regional governance, the driver limits and trade-offs associated with regulating the resource are realised. More widely, this approach represents an adaptable framework that explores the resilience of social-ecological interactions and feedbacks underpinning regional sustainable development.

KEYWORDS

Chilika lagoon; Natural resource management; Plausible futures; Safe and just operating spaces; Social-ecological modelling

1. INTRODUCTION

The challenges facing Earth's contemporary social-ecological systems (SESs) call for integrated, holistic and dynamic assessments of sustainability (van der Leeuw et al., 2011). However, predicting the future of SESs is associated with spatiotemporally complex processes like human population growth, climate change and natural resource use. Consequently, achieving aspirational futures such as the United Nation's Sustainable Development Goals and the Convention on Biological Diversity's "Aichi targets" is complicated by interplay between short-term policies, medium-term socioeconomic demands, long-term environmental trends and multiscale uncertainty about the future.

Empirical datasets have traditionally uncovered the complexities of real SESs, such as historical legacies, interdependencies and nonlinearities (Dearing et al., 2015). Yet, there is growing recognition that decision-makers benefit from complementing empirical data with modelled assessments that capture the complex processes driving social-ecological functions (Letcher et al., 2013; Schlüter et al., 2012). Ultimately, social-ecological models aim to test hypotheses about past causes of environmental degradation and provide virtual platforms to test strategies for management without the need for potentially harmful *in situ* experiments.

The non-analogous challenges facing SESs in the 21st century demand modelling techniques that move beyond statistical-based forecasts, optimisation and cost-benefit analysis, to process-based models for persistence, adaptability and resilience (Letcher et al., 2013; Verburg et al., 2016). For instance, unprecedented rates of regional interconnectivity are undermining resilience to cross-scale processes, such as “roving bandits” that sequentially exploit marine fish stocks (Berkes et al., 2006), and the effects of climate change on hydrological baselines and extremes (Milly et al., 2008). Moreover, the strengths of reinforcing and balancing feedback structures are known to evolve as systems adapt to stresses (Liu et al., 2007). Rather than assuming unidirectional relationships, as common amongst integrated assessment models used to estimate the socioeconomic impacts of climate change (Weyant, 2017), it is critical to capture feedbacks driving SESs towards abrupt ecological changes. Feedback sensitivity may be tested by probabilistic simulations that stress the system over a spectrum of future scenarios, with their iterative nature helping to improve model performance by repeatedly comparing outputs to new observations (Dietze et al., 2018). In turn, rather than narrowly forecasting the most likely future trajectory, normative scenarios can identify broad pathways leading to desirable futures whilst avoiding system limits (Bai et al., 2016). Although established in theory, the practical application of these concepts to real SESs is limited.

The conceptual framework of this research aims to bring together and advance three research areas in SESs science. First, with regards to operationalising desirable futures (Carpenter et al., 2015a), the planetary boundaries concept represents a complex systems framework describing a "safe operating space" (SOS) of nine Earth system limits which once transgressed weakens the chances of persisting stable Holocene environmental conditions (Rockström et al., 2009). Whilst there is debate over the global threshold values, interdependencies and implications for biodiversity (Brook et al., 2013; Montoya et al., 2018), the heuristic has been downscaled to identify coupled boundaries of regional biophysical limits and foundations of social wellbeing (Dearing et al., 2014; Raworth, 2012). To date, these "safe and just operating spaces" (SJOS) have been empirically defined in China (Dearing et al., 2014) and South Africa (Cole et al., 2017), showing how socioeconomic development can force ecosystem services (e.g. air quality, soil stability, biodiversity) beyond environmental thresholds and envelopes of historical variability. Therefore, this work aims to build on the empirical studies by converting the SJOS concept into a forward-looking tool that identifies driver-based SJOSs for regional social-ecological systems, defined by: (i) the future dynamics, interactions and limits of drivers underpinning regional social-ecological functions, (ii) the effects of non-stationary driver interactions, feedbacks and trade-offs, and (iii) the internal leverage points available to regional governors to shape system resilience.

Second, this study aims to build on previous attempts to model safe spaces of experimental (Carpenter et al., 2015b) and real systems (Hossain et al., 2017). In particular, the model of rice produce in Bangladesh (Hossain et al., 2017) is solely dependent on user-defined damage functions and statistical driver-response relationships that might breakdown under nonstationary environmental conditions. Here, a model of a real SES is built with a systems-based approach using empirical observations, qualitative records and insights from stakeholder interviews to capture the dynamics of the key stocks, flows and feedbacks (graphical abstract, panel 1). Once the model's skill is verified against historical data, the model is simulated forward under a spectrum of socioeconomic and biophysical scenarios to understand the likelihood of achieving safe and just futures from today (graphical abstract, panel 2). Outcome trajectories are then traced back to their causal driver pathways to understand the resilience of the system to cross-scale processes, feedbacks and management options (graphical abstract, panel 3).

In doing so, the third contribution of this research is building on the systems models that test resilience against a single temporally dynamic driver (Bueno and Basurto, 2009; Moxnes, 2000), and/or assume that the natural environment remains static whilst socioeconomic drivers vary over time (BenDor et al., 2009; Martins et al., 2015). Identifying SJOSs of multiple interacting drivers works towards overcoming three barriers resisting the use of SJOSs in regional decision-making, namely (a) the need for systems to transgress safe spaces before sustainable limits can be empirically observed, (b) the identification of a "core SJOS" of the least riskiest pathways of the most influential drivers, and (c) the development of a modelling approach that delivers realistic and robust governance options with respects to system complexities and uncertainties (Anderies et al., 2004).

On top of exploring the issues surrounding the future persistence of India's Chilika lagoon (i.e. the fourth aim of this paper), the system acts as the vehicle to develop and test this modelling framework. Section 2.1 introduces the study site, section 2.2 details the parameterisation of the systems model, before sections 2.3, 2.4 and 2.5 describe the external future scenarios, internal governance scenarios and definitions of safe and just futures, respectively. Section 3.1 simulates the future fish catches and their causal driver trajectories (section 3.2), before identifying driver-based SJOSs that represent interacting signposts to maintain SESs inside sustainable limits (section 3.3).

2. MATERIAL AND METHODS

2.1 The Chilika lagoon fishery system

The Chilika lagoon is Asia's largest brackish water ecosystem, covering 1,000 km^2 of India's Bay of Bengal coastline (Fig. 1). The fishery was valued at US$25-million/year in 2015, supporting 35,000 fishers and 200,000 livelihoods in the preparation, marketing and distribution of fish (Kumar and Pattnaik, 2012). Fish catch quadrupled between the 1930s and the late-1980s, but reversed from an average of 7200 tonnes/year during the 1980s to

3100 tonnes/year during the 1990s. Since 2005, catches have averaged 12,000 tonnes/year following the opening of a new tidal outlet in 2000 between the lagoon and the Bay of Bengal.

The history of multidecadal growth, collapse and recovery reflects Chilika's dynamic biophysical, socioeconomic and institutional settings. Chilika receives freshwater inputs from both the Lower Mahanadi catchment (LMC) and the Western Catchments (WC) on the lagoon's western flank (Kumar and Pattnaik, 2012) (Fig. 1), split 75:25 in favour of the LMC. Brackish ecosystem conditions are primarily maintained by the transgression of marine waters via the principal tidal outlet at Satapada. The location of the tidal outlet is dynamic, driven by the deposition of terrestrial sediment and northwards littoral drift along the Bay of Bengal (Chandramohan et al., 1993). In turn, it is estimated that 70% of the fish stock annually migrate to (anadromous species) or from (catadromous species) the lagoon via Satapada to complete reproduction cycles (Kumar et al., 2011). The 1990s fishery collapse is blamed on the unchecked northward drift and sedimentation of the now defunct "Magarmukh" outlet, whereby the reduced tidal range constrained fish migration, freshened water salinity to ~4 parts per thousand (ppt) and promoted the growth of freshwater vegetation which blocked fishing grounds (Kumar et al., 2011).

Concurrently, the active fisher population has increased from 7000 in the 1940s to 35,000 at present, split 60:40 between traditional and non-traditional communities (Kumar and Pattnaik, 2012). Non-traditional fishers introduced outboard motors in the early-1980s (Mishra and Griffin, 2010), with motorboats now representing ~40% of the 5600 crafts (Mohanty et al., 2016). Compared with traditional wind-assisted boats, motorboats enable daily commutes to fishing grounds further from landing centres. Regarding system management, resource access was moderated by cooperatives allocating fishing grounds to fishing villages throughout most of the 20th century (Adduci, 2009). The formation of the Chilika Development Authority in 1992 started an era of ecological monitoring; however, Chilika's formal institutional structure remains monocentric and hierarchical (Mishra and Griffin, 2010), with the CDA embedded within Odisha's Directorate of Fisheries and

Directorate of Environment. Moreover, Chilika is a common-pool resource, meaning the exclusion of potential fishers is difficult and the actions of user can potentially affect the welfare of others (Nayak and Berkes, 2011). Therefore, this status has historically limited the introduction of new fishing regulations on top of pre-existing state-level regulations outlawing the use of 'zero nets'. Consequently, the extent to which the system is resilient after opening the new tidal outlet in 2000 is unknown, supporting the need for a modelling study that explores the resilience of the system both in its current configuration and under alternative governance approaches. In other words, to what extent can decommonisation build resilience against the individual and driver combinations, thus expanding the driver-based SJOSs?

Therefore, modelling the Chilika lagoon has real-world, systems and practical rationale. First, efforts to model the system's persistence and guide its future governance are supported by its legacy of resource collapse and future uncertainties, including the magnitude and rate of climate changes; the extent to which biophysical changes will affect socioeconomic outcomes; and, the management approaches building resilience against potential social-ecological changes. Second, Chilika's SES presents challenges from a systems perspective, including the contrast between a well-defined physical boundary (i.e. the lagoon's banks) and various external processes (e.g. freshwater inputs and fish price); the emergent effects of different processes with different timescales (e.g. frequency of fishing trips); and, the interactions between numerous social-ecological feedbacks (section 2.2). Third, Chilika has a rich history of observational records, including annual fish catch records since the 1920s (Iwasaki and Shaw, 2009). This level of data availability provides diverse insights into system dynamics, including patterns of drivers and outcomes over time to inform model parameterisation and evaluation.

2.2 The social-ecological model

A social-ecological model was built in the modelling software STELLA v10.1 (ISEES, 2015) to address the regional sustainability challenges and operationalise driver-based SJOSs.

Systems modelling suits systems of stocks, flows and feedbacks, whereby the links between variables can be expressed as ordinary differential equations (appendix A) (Ford, 2010). Systems models are not usually regarded as forecasting or optimisation tools; rather, they investigate the combined effects of system drivers, feedbacks and policy levers (Chapman and Darby, 2016; Ford, 2010). STELLA provides an icon-based interface to design system diagrams, write equations describing the flows of *stuff* around a system (i.e. water and fish) and run simulations. Model outputs were recorded using STELLA's 'table-pad' function, before being exported and stored as comma-separated values (CSV) for graphing and analysis in the statistical software R (2008).

The modelling framework stresses the model under an array of plausible external (section 2.3) and governance scenarios (section 2.4) to distinguish between the internal pathways and feedbacks leading to the SJOS, and those leading to undesirable social-ecological futures characterised by declined catches, degraded fish stocks and livelihood losses (section 2.5). The model's specifications were based around this central aim. As detailed below, the key environmental and socioeconomic drivers of Chilika's fishery system were identified from regional literature and monitoring studies, plus qualitative insights from seven key-informant and twelve stakeholder interviews during a field visit to Odisha from February-April 2016. From this conceptual model, the 2060 simulation horizon aims to provide the system with enough time to collapse whilst capturing the effects of processes with different temporal scales (Dearing et al., 2012). The model's monthly resolution then aims to balance the computational requirements of the model (e.g. number of iterations per simulation) with the need to capture the temporal scales of the processes potentially collapsing the system, such as the seasonal ecosystems variations from monsoonal freshwater inputs. The rationale behind the model's system-wide spatial specification reflects: (a) the lack of spatially disaggregated data on Chilika's fish stocks, human populations and fishing stresses, (b) the lack of a holistic systems model that combines emergent stresses across Chilika, and (c) the trade-off between the number of model variables and the model's computational efficiency.

The rest of section 2.2 provides an overview of the materials and methods used to parameterise and evaluate the seven key drivers of fish catch (Fig. 2), although the reader is directed to appendix A, appendix B and Cooper (2018) for the full numerical values and evaluation techniques.

2.2.1 Environmental drivers

Based on the dual-stock model of Bueno and Basurto (2009), a reinforcing feedback connects mature and juvenile stocks, whereby the number of new juvenile fish per month is a function of: (i) the mature population in the previous month; (ii) fish fecundity, reproductive life length, life expectancy and immaturity duration parameters, all altered from default to reflect Chilika's resource size (appendix A1.3), and (iii) a density-dependent survival rate (Ricker, 1975), equalling the ratio between the fish population and the ecological carrying capacity, which in turn defines the maximum fish population supportable by the lagoon (CIFRI – unpublished).

The three biophysical stresses (outlet sedimentation, fish survival and aquatic vegetation coverage) are all influenced by Chilika's freshwater and sediment flows, which are generated by rainfall across the LMC and WC. Adapted from Ghashghaei et al. (2013), parameterisation of the LMC's rainfall-runoff relationship uses monthly discharge data from the Tikarapara gauging station (Fig. 1), as recorded by the Indian Central Water Commission from Jan 1973-Dec 1982. Corresponding monthly rainfalls from the districts of Angul, Baudh, Sambalpur and Sonepur (LMC), and Khordha and Puri (WC) were acquired from the Indian Meteorological Department. In turn, runoff evaporation is a function of monthly near-surface air temperature (Linacre, 1977). Monthly LMC sediment load is derived from a sediment-rating curve from observations upstream of Cuttack (Mishra and Jena, 2015). This relationship is then downscaled to reflect the 30% contributions of the WC (Kumar and Pattnaik, 2012). Sediment exits Chilika's sediment stock at 0.13 x 10^6 tonnes/year (Kumar and Pattnaik, 2012), with monthly removal proportional to freshwater delivery (appendix A1.6).

Ecohydrological conditions are modelled using graphical functions, which hypothesis driver-response relationships in the absence of temporally coherent data (i.e. monthly freshwater inputs and seasonal salinity records). Following the guidelines of Sterman (2000), such as the need for known reference points and extremes (i.e. salinity ≥0 ppt), graphical functions relate monthly freshwater inputs to lagoon-wide salinity and dissolved oxygen, the effects of outlet sedimentation on salinity and the consumption of oxygen by aquatic vegetation (appendix A1.5). As a well-mixed shallow lake, a linear model (r^2 = 0.89, $p < 0.05$, df = 38) relates water and air temperatures, derived from monitoring records of the Chilika Development Authority (CDA) from September 2006-December 2009.

Monthly salinity, dissolved oxygen and temperature then influence the default juvenile survival rate via known reference points (appendix A1.5.4), such as the knowledge that 20% of the fish stock, as freshwater species, would be resilient to freshwater conditions (Kumar and Pattnaik, 2012). In turn, approximately 70% of the fish stock annually migrate to and from the lagoon to complete reproduction cycles (Kumar et al., 2011), meaning the fish population and its rate of renewal are coupled with the lagoon's sedimentation dynamics. It is assumed that the outmigration of the migratory stock is split across the year, with the number of in-migrants inversely proportional to Chilika's sediment stock in any given month. Lastly, aquatic vegetation is modelled as a stock to capture the positive feedback with lagoon sedimentation: fluvial sediments provide nutrients for macrophyte growth; the trapping effect of macrophyte coverage then promotes the deposition of fluvial sediment (Jaikumar et al., 2011; Panda et al., 2015). The monthly fishing effort of each fleet is then modulated by the vegetation coverage, simulating the ecological refuge provided by blocked fishing grounds.

2.2.2 Socioeconomic drivers

Four socioeconomic feedbacks drive fisher population growth, motorboat usage, the days fished each month and the catch of juvenile fish. The traditional and non-traditional fisher populations are driven by externally generated birth and death rates until the carrying capacities of each fleet (equal to the economic value of catch divided by the average livelihood cost) are exceeded (Fig. 2, blue). The carrying capacities represent simple limits on the number of financially supportable livelihoods, based around the average income of each fleets and the minimum cost to fish. Surplus fishers exit the system once a carrying capacity is exceeded, akin to the livelihood losses of the 1990s collapse (Nayak and Berkes, 2010).

The motorisation of traditional boats by relatively affluent fishers drives the intensity of fishing efforts (Fig. 2, orange). The number of traditional fishers upgrading to motorboats each month equals the proportion of traditional fishers with income greater than the cost of motorised fishing (appendix A1.4.4). Income is assumed normally distributed, as relatively few traditional fishers can currently afford motors (Kumar and Pattnaik, 2012). Upgrades only occur if profitability falls, reflecting the desire expressed by the fishers interviewed to persist traditional practices when economically viable.

Traditional fishers operate in weekly cycles due to longer travel times to catch grounds, effectively fishing for five days before returning to landing centres (Kumar and Pattnaik, 2012). In contrast, it is assumed that motorboats operate daily, only limited by religious festivals (~17/year). The key-informant interviews suggested that fishers adapt fishing efforts to perceived stock abundance (Fig. 2, red). Therefore, type-II functional responses (Holling, 1959) link the days fished each month to the underlying fish density (appendix A1.4.1). Finally, fishers stated that the acceptance of juvenile catch increases during stock declines to compensate for lost fishing days. Therefore, the model diverts the difference between the fishing effort at maximum days fished and the fishing effort at time *t* to the withdrawal of juveniles (Fig. 2, pink).

2.2.3 Model evaluation

A model based on best available knowledge is not necessarily a useful decision-making tool (Sterman, 2000). Cooper (2018) conducted nine tests to assess whether the model captures reality for the right quantitative and qualitative reasons. As the most informative technique, designed to assess the contribution of each driver to outcome dynamics, the process of generalised sensitivity analysis (Spear and Hornberger, 1980) is described here.

Based around two stages, generalised sensitivity analysis first simulates the historical reference period while randomly perturbing key driving variables (*j*, n=25) by error ranges (ε_j) between ±50% of their parameterised values (Appendix A). The non-parametric Kolmogorov-Smirnov test (Massey, 1951) then identifies variables with significant differences between the subsets of ε_j reproducing the reference mode and the subsets of ε_j failing to reproduce the reference mode. It is assumed that the critical determinants of model behaviour will display the greatest disparity between behaviour-giving and behaviour-missing subsets of ε_j. Overall, 6 variables are found to critically determine whether the model reproduces reality (table 1), corresponding to total resource availability, the dampening of fishing efforts by aquatic vegetation, fishing boat numbers, freshwater and sediment deliveries, and outlet sedimentation. These variables align with the narrative that the 1990s collapse was driven by the effects of outlet sedimentation on fish migration and habitat quality.

Second, the critical drivers were perturbed by ±5%, ±10%, ±20% and ±30% to bind acceptable error ranges. As expected, the degree of similarity between model outputs and observations weakens as errors widen (Fig. 3). Positively, the ±5% error range reliably reproduces the periods of catch stability, collapse and recovery, as well as the observed salinity (Fig. 3A) and aquatic vegetation (Fig. 3B) trends which influence fish renewal and catch, respectively. Therefore, the most influential model drivers match our qualitative understanding of the system, whilst also reproducing reality within permissible error ranges.

2.3 Plausible external trajectories

The future resilience of the Chilika lagoon is assessed under a spectrum of plausible driver evolutions and interactions. Per governance scheme (section 2.4), the model generates 1000 exploratory scenarios for monthly precipitation and near-surface air temperatures across the LMC and WC, average fish and diesel price, and the human population growth rate 'r' (appendix C). The first 444 months (1973-2009) use historical data when available (appendix A), before projecting until 2060 under the exploratory scenarios sampled from uniform probability distributions between minimum and maximum plausible changes (table 2). The scenarios are 'seeded' in STELLA to ensure that the governance scenarios are stressed under the same array of external trajectories.

Rather than downscaling global climate models, future monthly rainfalls and temperatures (*c*) at time *t* are generated internally:

$$MonthlyClimateConditions_{c,t} = ECDFValue_{c,t} + FinalClimateChange_c \times \frac{n}{N} \quad \text{(Eq. 1)}$$

$ECDFValue$ is randomly sampled from cumulative distribution functions of monthly rainfall and temperature from 1973-2009 (appendix A1.6), as recorded by the Indian Meteorological Department, and $FinalClimateChange$ is randomly sampled between zero, and the magnitudes of rainfall and temperature change predicted by RCP8.5 (IPCC, 2013) for Odisha by 2065 (table 2). To generate smoothly increasing trajectories, n is the number of months since January 2010 and *N* is the total number of months between January 2010 and December 2060.

The export of Chilika's catch to domestic and international markets has decoupled fish price from resource availability (Nayak and Berkes, 2014). Diesel price is also assumed to be determined by international markets rather than regional supply and demand. The model produces linear fish and diesel price trajectories (*m*) by adding the randomly sampled scenario gradient (table 2) to the value of the previous month:

$$Price_{m,t} = Price_{m,t-1} + \frac{PriceIncrease_m}{12} \quad \text{(Eq. 2)}$$

Simulating a random trajectory each year would investigate the effects of volatile markets; however, the number of Monte Carlo trajectories per plausible future would increase from 5 to 255, with deleterious impacts on computational efficiency.

Lastly, the trajectories of human birth and death rates are assumed free from governance influence. To uncover the boundaries of Chilika's RSJOS, population growth is designed to force the fisher population towards unsustainable levels (table 2).

2.4 Internal governance scenarios

The model provides a virtual laboratory to explore how lagoon management can affect the driver-based SJOSs. Options prior to the fieldtrip included ‘doing nothing’; business-as-usual outlet maintenance; restrictions on fishing area and/or time; licence limits; motorboat bans; quotas and alternative livelihoods. Discussions with Chilika’s experts identified infeasible policies given Chilika’s socio-political context, such as the implementation of quotas and fishing licences, which were thought to limit the livelihoods of existing fishers and the entry of new fishers. Therefore, the three approaches outlined below were deemed to best balance the ecological integrity of the lagoon with the quality of fishery livelihoods (the model outputs help assess the extent to which this rationale is true):

- **Governance scenario 1.** Business-as-usual outlet maintenance (OM): the CDA plans to cut a new tidal outlet every ten years to renew fish migration and lagoon salinity (Kumar and Pattnaik, 2012). As per the opening in 2000, we assume that future openings will return sedimentation to pre-1980s levels. This approach is preferable from the standpoint of minimising interventions, as it does not limit the number of fishers or the spatiotemporal scales of their activities.
- **Governance scenario 2.** OM plus a year-round tidal outlet fishing ban (OB) starting in 2015 but taking until 2025 to fully materialise as cooperation gradually increases. From 2025, mature fishing effort is reduced by 7% relative to OM, equalling the area of the tidal outlet relative to the lagoon.
- **Governance scenario 3.** OB plus alternative livelihoods (OL): fishers also exit the system at an exploratory rate of 1/1000 fishers/month to limit fishing efforts and reduce livelihood dependency on the lagoon (note: the model does not simulate the dynamics of the alternative livelihoods once the fishers have left the system). This scenario starts in 2015 because Odisha’s state government and Integrated Coastal Zone Management Project currently generate alternative livelihoods.

An alternative approach would be to model adaptive governance that implements remediation when necessary, such as opening the outlet or implementing bans once catch is undesirable. However, static scenarios are modelled here because decision-makers are prioritising wise-use and maintenance from today (Kumar et al., 2011). Moreover, modelling a limited number of governance scenarios helps to improve the tractability of the driver-outcome relationships, while establishing foundations to implement adaptive policies in future.

2.5 Defining safe and just futures

Defining desirable system functions is critical to gauging future sustainability (Levin et al., 2015). To this end, Dearing et al. (2014) identify SJOS limits from linear and nonlinear trends, thresholds and early-warning signals observed in empirical records. We use linear SJOS definitions here for three reasons. First, fisheries have multiple outcomes which should remain safe and just, including catch, resource availability, and broader components of socioeconomic wellbeing. However, the CDA currently judge the sustainability of fishing efforts against maximum sustainable yield (MSY), conceptualised as the maximum catch that is indefinitely extractable from a fish stock without degrading its long-term renewal (Maunder, 2008). Second, linear thresholds are time-invariant, meaning falling beneath standards such as calorific intake or per capita income is undesirable at any time. Third, the linear boundaries provide an initial proof of concept to judge the efficacy of this modelling framework before including more complex nonlinear thresholds.

We identify three operating spaces based on the evolution of fish catch relative to contemporary baselines and environmental limits:

— **Safe and just*:*** from 2050-2060, annual catch averages between 11,400 tonnes/year and 13,900 tonnes/year, equalling the lower and upper estimates of MSY (Kumar and Pattnaik, 2012). MSY balances stakeholder desires for sustainable livelihood generation, income and food security, with the maintenance of ecosystem functions.

- **Dangerous:** at any time, the total fisher population exceeds the total livelihood carrying capacity (appendix A1.4.1) – signifying ecologically unsafe resource degradation and potential livelihood losses.
- **Cautionary:** annual catch from 2050-2060 averages (i) above MSY; or (ii) below MSY, although in the case of the latter, the economic benefits of catch still cover the average livelihood costs of fishing.

3. RESULTS

3.1 Future catch trajectories

Business-as-usual (OM) governance displays least resistance to external and internal drivers (Fig. 4A), with only 12% of futures achieving safe and just catch, and 36% triggering livelihood losses by 2060. In contrast, dangerous futures are absent when common-pool rights are restricted under OL governance (Fig. 4C). Therefore, it is hypothesised that a proportion of OM's dangerous futures are caused by unsustainable fishing efforts, which become sustainable with the introduction of fishing regulations and alternative livelihoods.

Governance also influences the timing and abruptness of catch declines (Fig. 4). Dangerous futures generally occur earlier under OM, with the year of fisher overcapacity ranging from 2050-2060 (mean = 2056), rather than 2052-2060 (mean = 2058) under OB. However, collapsing from 8,000 tonnes/year to 2,000 tonnes/year takes an average of 12.0 and 10.5 years under OM and OB, respectively. This tentative inverse relationship between the onset and rate of catch decline questions whether decision-makers would prefer *earlier-but-gradual* or *later-but-abrupt* system degradation. Furthermore, whilst the system historically appears robust to sporadic catches above MSY, model outputs suggest that the persistence of Chilika's resource stock by mid-century is undermined by near-term future overexploitation. Dangerous futures average 14,300 tonnes/year from 2020-2029 under both OM and OB governance, while safe futures average 13,800 tonnes/year and 13,400 tonnes/year, respectively.

3.2 Causal driver pathways

The driver time-series represent multidimensional pathways coupled within system space (Fig. 5), meaning that reaching desirable futures requires the safe and just pathways of all drivers to be followed simultaneously. In general, the future safety of Chilika is found to be inversely proportional to the gradients of fish price, total fishers, motorboats and juvenile catch; for example, the SJOS of OM governance (Fig. 5, left column) corresponds to less than 6000 motorboats by 2050, whilst the dangerous space starts around 7300 motorboats. Contrastingly, safe and just futures may be achieved across the entire ranges of annual rainfall and vegetation coverage trajectories.

Fish catch safety is also dependent on driver interrelationships, such as the simultaneous need for motorboats to represent less than 60% of total boats (OM), and the proportion of juvenile catch in total catch to remain below 3%. In turn, increased fishery regulation builds system resilience against socioeconomic drivers and their relationships, exemplified by the 33% increase in the permissible number of motorboats under OL governance relative to OM. Moreover, OL governance builds robustness against the nonlinear fisher population and motorboat trends that cause cautionary and dangerous pathways under OM and OB governance schemes. Finally, the distinctness of each space indicates the confidence with which following a given trajectory should result in the intended outcome. For example, a fish price of >700 Rs/kg by 2050 under OM corresponds to a fuzzy mixture of cautionary and dangerous futures; contrastingly, keeping the number of motorboats below 5000 is distinctly safe.

Despite identifying multidimensional pathways to follow between now and mid-century, the fuzzy nature of the time-series hampers the precise identification of SJOS limits, because (i) different trajectories of the same driver may reach the same outcome state (*equifinality*), and (ii) near identical driver trajectories may produce different outcome states (*multifinality*), depending on the simultaneous trajectories of other drivers.

3.3 Driver-based (core) safe and just operating spaces

To address the limitations outlined above, this section defines driver-based SJOS using conditional probability plots charting the proportion of different futures (i.e. safe and just, cautionary and dangerous) over the trajectory ranges. Each conditional probability plot has two dimensions (Fig. 6): (i) the value of each driver in 2050 (from Fig. 5), and (ii) the proportion of different futures from 2050-2060 over the driver range. The plots can be divided into those that have SJOSs ($\%_{SJOS}>0$) across the entire range of driver trajectories, and those with particular trajectories associated with no SJOSs ($\%_{SJOS}=0$). Consistent with the driver time-series, the socioeconomic drivers (Fig. 6, rows 2-6) under OM and OB governance all have SJOS limits, whilst the two biophysical drivers (Fig 6, rows 1 and 7) have unrestricted SJOS trajectories across OM, OB and OL.

The most influential drivers are marked by the steepest changes in safety and the greatest degree of separation between safe and dangerous trajectories (as measured by the Kolmogorov-Smirnov statistic, *k*). For example, under OM, the proportion of safe futures falls from 75% to 0% as the number of motorboats by 2050 increases from 5000 to 7000. In turn, the proportion of dangerous futures increases from 0% to 100%, as the number of motorboats range from 7000 to ~10,500 by 2050. Beneficially however, OM's safe and dangerous spaces are intersected by a distinct cautionary window between 6000-7000 motorboats, representing a space to remediate trajectories that have exceeded the SJOS. Less influential drivers display weaker separation between safe and dangerous spaces; for example, the safety of a given fisher population by 2050 partly depends on the concurrent number of motorboats. For instance, 60,000 fishers by 2050 must occur with less than 5500 motorboats (<55% of total boats) to give OM any chance of the SJOS.

The concept of a "core SJOS" was introduced by Steffen et al. (2015), who argue that climate change and biosphere integrity are the two planetary boundaries with independent capacities to drive state changes in the Earth system. We operationalise core SJOSs for regional SESs by cutting through the complexity of interacting driver ranges and probabilities, identifying the safest multidimensional pathways giving ≥75% chances of safety

(Fig. 6, green fills). The most influential drivers with individual safety proportions ≥75% represent the core foundations for decision-makers to target, with the remaining dimensions defined by the corresponding pathways of all other drivers.

The proportion of simulations per governance scenario reaching the core SJOS gives a relative measure of the core space size. The cores of OM, OB and OL measure 0.9%, 2.8% and 71.2% respectively, again illustrating that the most regulatory governance approach gives the best chance of remaining inside the SJOS. In general, the core SJOSs depend on narrow ranges of motorboats and juvenile catches; for instance, under OM and OB, motorboat numbers must fall within 4200-4600 and 4800-5000 by 2050, respectively. Fish price can reach 280 INR/kg by 2050 under OM before the chances of reaching a safe future fall beneath 75%. Remaining within this limit requires a shallowing of the fish price trend from 2009-2014, as the core space will be exceeded by 2025 if the 15 INR/year growth rate persists.

Promisingly, a continuation of the observed fisher population trend from 2009-2014 will fall inside the core by 2050 (~52,000 fishers); however, the core space of motorboats may still be surpassed if fewer fishers occupy each boat, perhaps if socioeconomic wellbeing improvements reduce the need to split fishing costs six ways. The insensitivity of the core SJOSs to rainfall change and aquatic vegetation coverage further emphasises the weakness of biophysical leverage points for decision-makers.

4. DISCUSSION

By projecting plausible external trajectories under alternative governance approaches, this modelling framework has illuminated desirable cross-scale processes, social-ecological feedbacks and internal driver limits for a system with a legacy of resource collapse. This section discusses the implications of applying this modelling framework elsewhere, the ways in which we evaluate the future of SESs and the wise-use of Asia’s largest brackish water ecosystem.

4.1 Adaptability of the modelling framework

It is important that modelling studies develop concepts and methodologies that are transferable to other systems (Verburg et al., 2016). Identifying future driver-based SJOSs elsewhere is dependent on three conditions. First, the central governance philosophy must be to persist social-ecological functions by achieving desirable levels of socioeconomic wellbeing without transgressing ecological thresholds. The framework becomes less useful if governors are only interested in forecasting the most likely short-term outcome. Therefore, decision-makers and modellers must be able to envision 'good Anthropocene' goalposts to shape the future system towards (Bai et al., 2016; Berkhout, 2014). Critically, achieving the safe and just futures as defined here does not rule out steering towards different trajectories in future (Hughes et al., 2017, Sterk et al., 2017), at least relative to the rigidity of ecological degradation and livelihood losses from fishery collapse. Whilst MSY presents a well-established target for fisheries, the framework is transferable to using optimum yield by considering regional socioeconomic and environmental constraints (Levin, 2014). However, such normative targets are not always readily definable, such as for ecosystem services like soil stability and water quality (Dearing et al., 2014).

Second, the choice of normative, nonlinear and/or hysteretic boundaries (cf. Dearing et al., 2014) is important for the framework's transferability. Defining Chilika's safe and just future through a historical envelope of variability would be inappropriate here given that catch collapsed as recently as the 1990s. Moreover, the dependent population and level of resource use have both increased by ~40% since the late-1980s, questioning the justness of limiting future catches to pre-collapse levels. Where normative conditions and historical windows cannot be defined, statistical breakpoints may detect future outcome shifts caused by abrupt feedback-driven or structural changes (Rodionov and Overland, 2005). However, nonlinearities are not always unsafe, as an abrupt catch decline in the future might reflect a livelihood shift away from fishing, rather than resource scarcity.

Third, coupling Monte Carlo simulations with normative targets evaluates the extent to which driving processes can diverge from today but still achieve desirable outcomes

(Folke, 2006). In turn, the non-binary thresholds caused by driver multifinality and equifinality build on the conventionally hard and static SJOSs (see Cole et al., 2014; Hossain et al., 2017), aligning the SJOS concept with multidimensional notions of resilience. The range of safe and just trajectories represent resilience *latitude,* denoting the range of driver trajectories that lead to desirable outcomes (Walker et al., 2004). In turn, *resistance* is the rate at which safety changes over the driver range (section 3.3). Future work may seek to formalise how system *precariousness* changes over time based on the model defined SJOSs, for instance, the product of the driver's distance from its SJOS edge (i.e. where $\%_{SJOS}$=0) and its current SJOS conditional probability.

Alternatively, using conventional predictive scenarios to define safe and just boundaries may have critically overlooked the holistic range of trajectories and interactions which drive the system into undesirable outcomes, particularly for feedback-dependent systems like fisheries and coral reefs where slightly altered driver magnitudes can trigger catastrophic impacts (Scheffer et al., 2001). However, models that are data and/or processor intensive (e.g. integrated assessment models) may not have the computation resources to generate plausible trajectory funnels.

4.2 Wider implications for modelling SESs

Assessing the quality of Anthropocene futures is a challenge for decision-makers given the complexity of social-ecological systems (Brugnach et al., 2008, Maier et al., 2016). Consequently, this proof-of-concept study develops an approach similar to a satellite navigation system used to guide vehicle drivers towards their desired destination. A safe and just future defined by experts, decision-makers and/or stakeholders represents the destination, whilst the exploratory scenarios are akin to the sat-nav assessing possible routes. Following the core safe and just pathways is analogous to a driver wanting to avoid hazardous routes. Furthermore, decision-makers are forced to think outside conventional reference frames; for Chilika, this means leaving behind the perception that solely rejuvenating resource mobility is sufficient to ensure long-term persistence. This quality is akin to a sat-nav discovering a new route which would have remained otherwise undiscovered.

In turn, it is imperative to evaluate whether the SJOSs identified by this modelling framework are accurate. Given the parametric uncertainties of the datasets (Cooper, 2018) and the potential for excluded drivers like extreme tropical storms to become important in future, the SJOSs designed here are framed as coupled social-ecological pathways of today's key drivers and feedbacks. To this end, replicating the complex historical pattern of catch stability, collapse and recovery within ±5% parametric errors (section 2.2.3) builds confidence in both the structure of the model and the accuracy of the parameterisation datasets and equations.

Using systems modelling sets a rigid system structure for each simulation, which is unable to capture the spatial distribution of fishing efforts and human agency. Alternative integrated approaches, either in the form of ready-made 'integrated ecological-economic fishery models' (Nielsen et al., 2017) or more modular approaches, such as coupling specialist fishery, water quality and/or supply chain models (Avadí et al., 2014; Townsend, 2013) may overcome this rigidity. However, integrated approaches have a number of inherent disadvantages for identifying SJOSs. Increased realism trades-off against increased data demands, model runtimes and reduced user-friendliness. 'Integronsters' may emerge from the coupling of discrete modules, meaning models become overly complex to parameterise, evaluate and communicate to decision-makers (Voinov and Shugart, 2013). Consequently, integrated approaches used without inputs from system models, such as future scenarios of special interest, are less suited to horizon-scanning undesirable interactions, feedbacks and nonlinearities across the spectrum of plausible system evolutions.

4.3 The future of the Chilika lagoon

Through the operationalisation of driver-based SJOSs, this study finds that the Chilika lagoon faces a choice between (i) business-as-usual governance and its associated risks of fishery collapse, and (ii) implementing transformational governance to widen permissible driver limits. Although it is possible to rank additional outcomes beyond fish catch like fisher incomes and catch-per-unit-effort, this strategy might risk offsetting underperformance (e.g. cautionary futures) against overperformance (e.g. short-term fishery profits) (Holden et al., 2014). Therefore, this study prioritises the achievement of a resilient system outcome over individual and potentially conflicting interests. However, in reality, all 3000 plausible futures are associated with trade-offs that question the extent to which the SJOSs are truly just. For instance, maintaining the system's common-pool status in the short-term may make limiting the number of motorboats unavoidable in the long-term, with the unintended consequence of isolating fishers requiring motorboats to reach distant grounds.

Moreover, the unregulated fishery is found to be vulnerable to the 'success to the successful' archetype (Senge, 1990), as steep fish price growth enables ~75% of the traditional population to upgrade to motorboats by 2025. The resulting loss of self-organizing social constraints allows the booming non-traditional population to dominate resource extraction (Ostrom, 1990), causing the marginalisation of traditional livelihoods and the spiky fisher population total. Therefore, preserving common-pool rights within the lagoon may require the introduction of non-fishery benefits to counteract the uptake of more exploitative practices.

Transformational governance (OL) also leads to similar trade-offs: for example, should alternative livelihoods target non-traditional communities despite their contributions to fishery value, or the more populous traditional communities which have fished Chilika for centuries? Increased regulation may make Chilika an "organic machine" (White, 1995), with catches becoming increasingly reliant on human interventions. Arguably this process is already underway, with the finding that periodic outlet opening decouples the future state of the fishery from biophysical driver trajectories.

Ultimately, Chilika's SJOSs exist within subsets of hydroclimatic, biophysical, socioeconomic and governance pathways. While we stop short of recommending specific pathways, regional decision-makers may use these concepts and horizon-scans to inform desired system identities and track the progress of drivers and outcomes towards desirable futures.

5. CONCLUSION

This study presents a novel framework to guide SESs towards safe and just futures by modelling internal driver dynamics under a spectrum of external trajectories, before classifying outcome time-series relative to today's social-ecological norms. In doing so, we find that whilst business-as-usual governance decouples the system from external biophysical changes, the Chilika lagoon fishery system in India is vulnerable to near-term nonlinear increases in the number of motorboats and plausible trajectories of multi-decadal fisher population growth. Therefore, the framework converts the retrospective 'safe and just operating spaces' concept into a forward-looking tool for proactive system governance, by identifying interacting signposts to manage drivers within sustainable limits and assess the resilience of alternative governance approaches.

The core SJOSs combine driver interactions to give decision-makers human-natural pathways with at least 75% chance of sustaining MSY by 2060. The core SJOSs guide decision-makers in the face of social-ecological complexity and uncertainty, exploring the association between driver trajectories and the possibility of safe and just futures. Consequently, we call for greater appreciation of the range of plausible pathways and driver interactions a system may take when modelling the future, helping to depict landscapes of outcomes, limits and governance options for regionally sustainable SESs.

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FIGURES

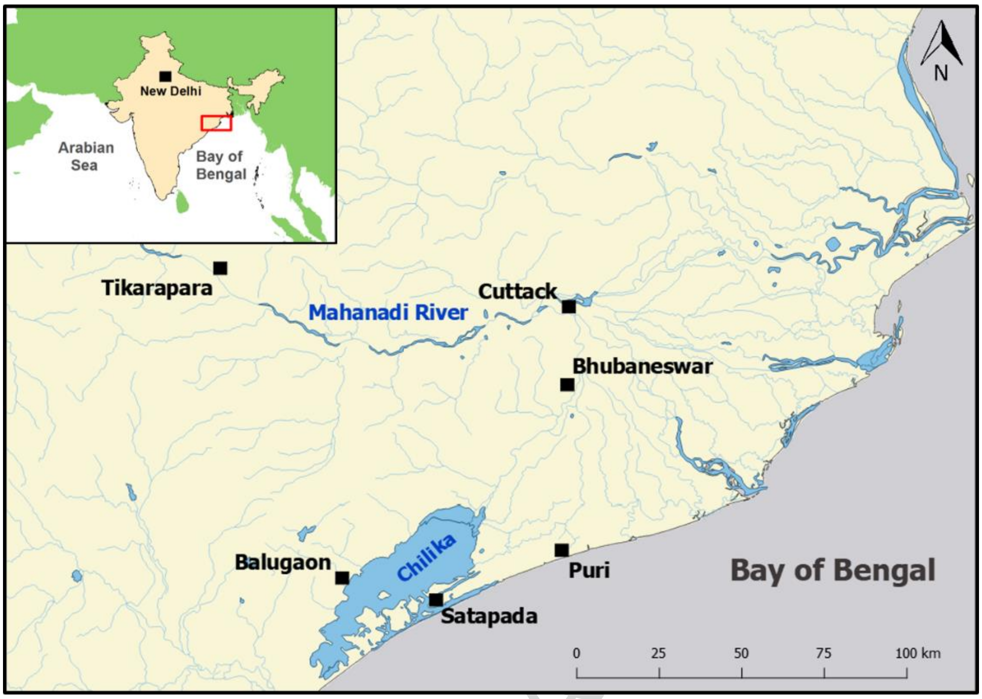


Fig. 1. The location of the *Chilika* lagoon within India (boxed inset), and its location relative to major urban areas in Odisha (main).

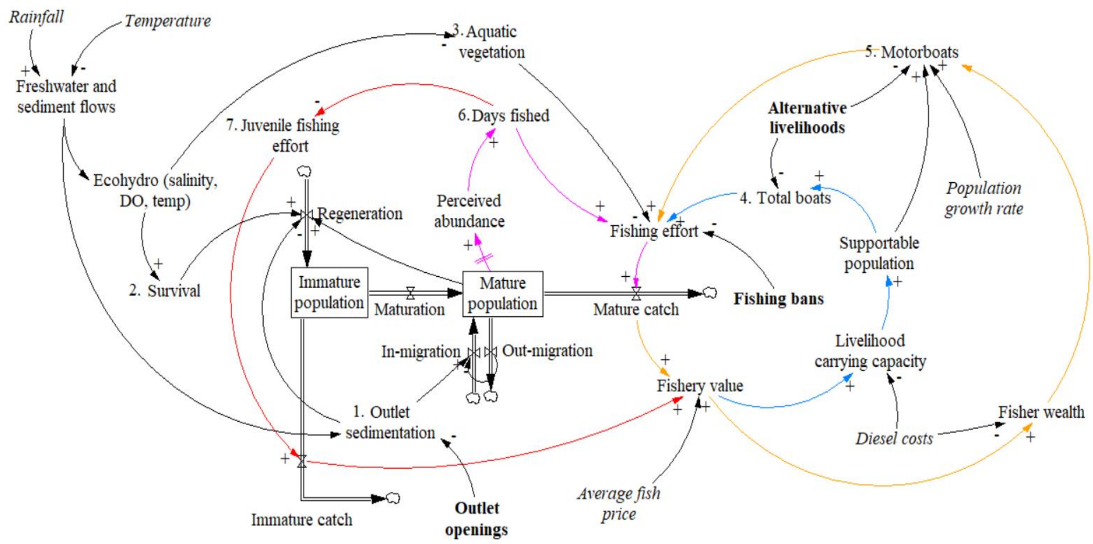


Fig 2. Conceptual diagram mapping the seven key modelled drivers of Chilika's immature and mature fish stocks. Driver key: italicised – external; bold – governance. Socioeconomic feedbacks: blue – total fisher population growth; orange – motorboat uptake by relatively wealthy traditional fishers; pink – days fished as a function of perceived stock density; red – increased juvenile catches to compensate for lost days fished. DO – dissolved oxygen. '+' positive driver-output polarity; '-' inverse driver-output polarity.

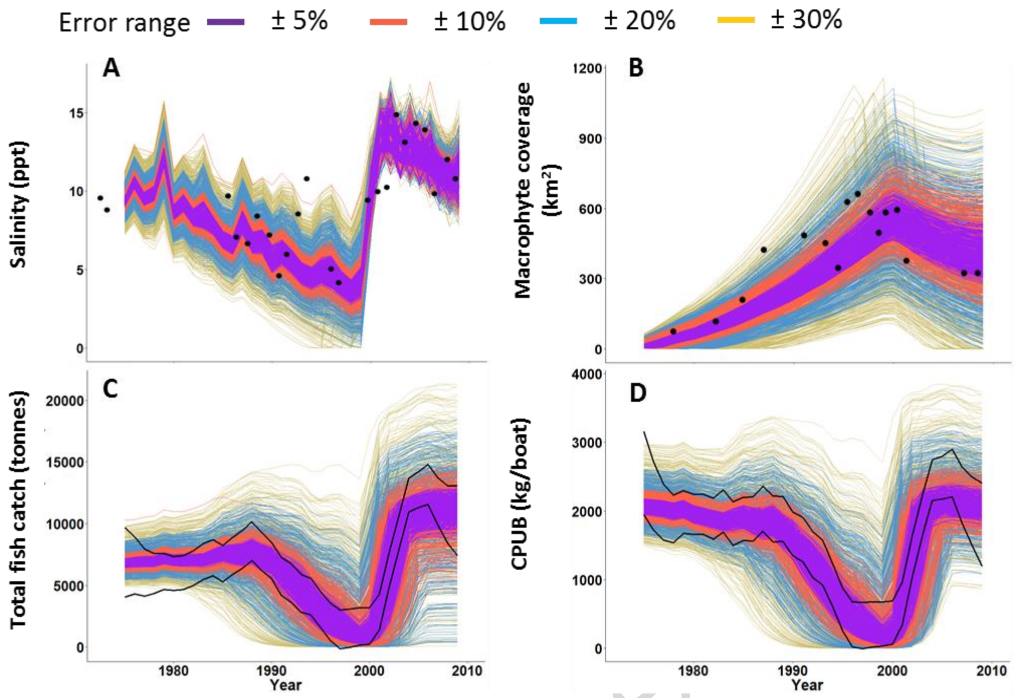


Fig 3: Graphical outputs from the second stage of generalised sensitivity analysis where the six critically sensitive variables (table 1) are simulated under four error ranges; 500 simulations are run per error range. Observations (black) are plotted against model generated time-series of four social-ecological processes: (A) salinity; (B) aquatic vegetation coverage; (C) catch (99% confidence intervals in black) (D) catch per unit boat (99% confidence intervals in black).

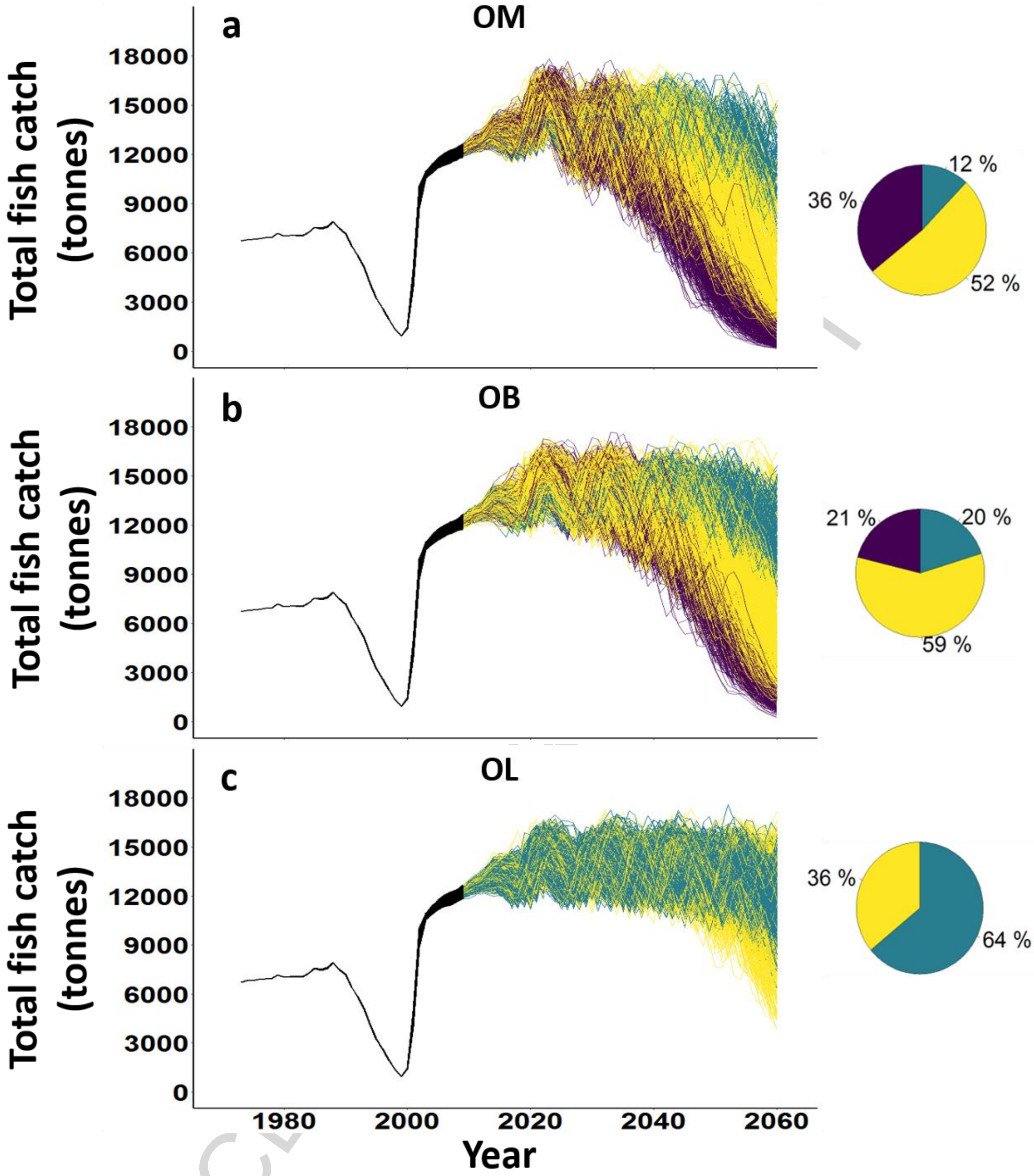


Fig. 4. Annual catch time-series and the proportions of plausible futures produced by the spectrums of driver interactions under the three governance scenarios (N = 1000 per scenario): 'OM' – outlet maintenance only; 'OB' – OM plus outlet fishing ban; 'OL' – OB plus alternative livelihoods. Normative futures: 'Safe and just' – green, 'cautionary' – yellow, 'dangerous' – purple and 'historical' – black. Colour-blind friendly scheme based on R package 'viridis' (Garnier, 2018).

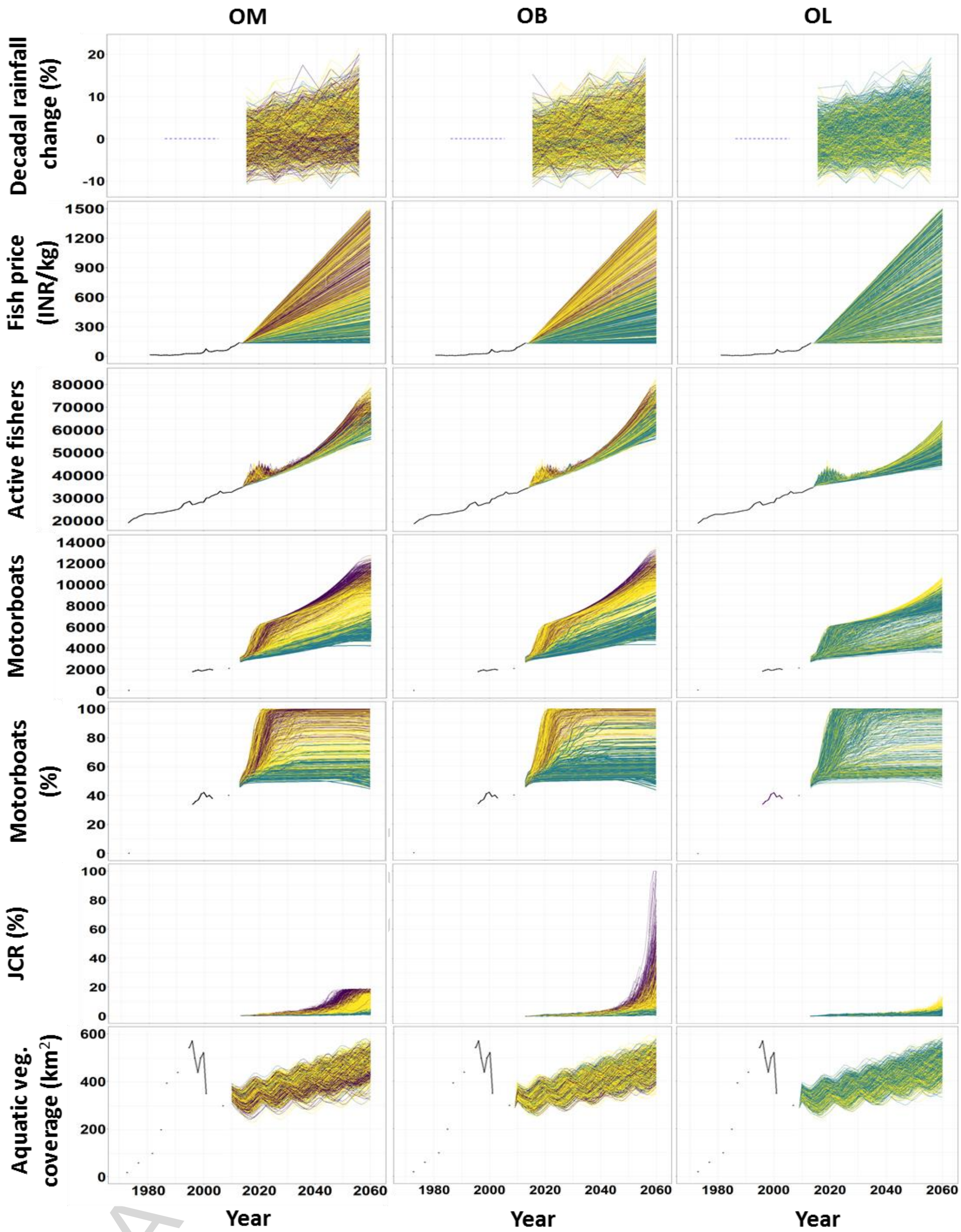


Fig. 5. Time-series depicting the safe and just (green), cautionary (yellow) and dangerous (purple) driver pathways of each plausible governance scenario. All model variables could be mapped in theory, but due to space limitations, only the critical socioeconomic drivers are shown here alongside two historically important biophysical drivers. Observed data (black) covers 1973-2009; time-series gaps represent missing data. JCR – Juvenile catch rate - the proportion of juvenile catch in total catch.

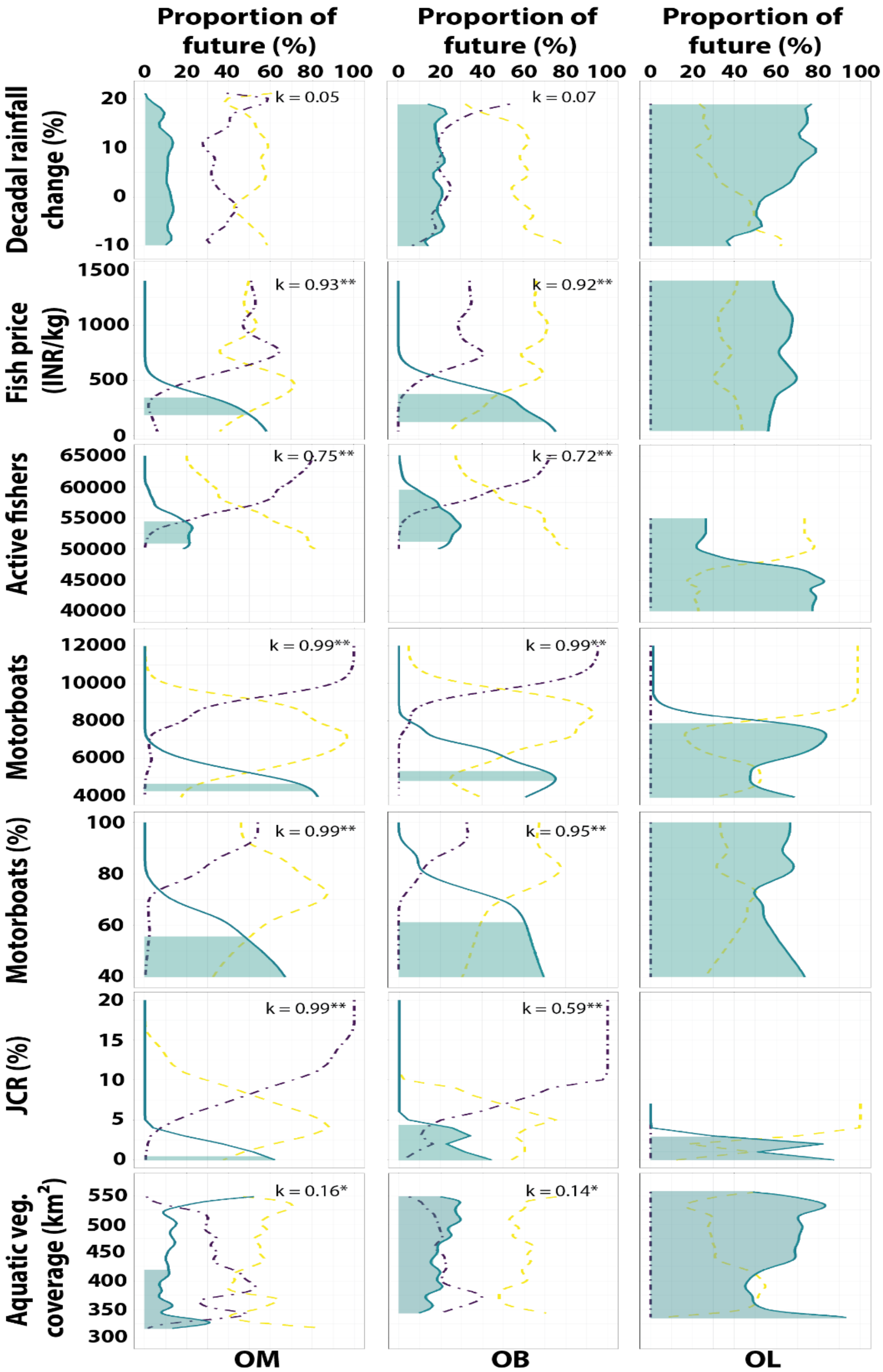


Fig. 6. Conditional probability plots relating the magnitude of fishery drivers by 2050 to the proportion of safe and just (green), cautionary (yellow) and dangerous (purple) futures. Driver magnitudes associated with safe and just futures (% = 100) denote the safest plausible trajectories, whilst a range without safe and just futures (% = 0) means that a driver has exceeded its driver-based SJOS. The core SJOS (green fill) shows trajectories that if simultaneously achieved give a ≥75% chance of sustaining MSY until 2060. k – Kolmogorov-Smirnov statistic. Significance levels: ** - p < 0.01; * - 0.01 ≤ p ≤ 0.1.

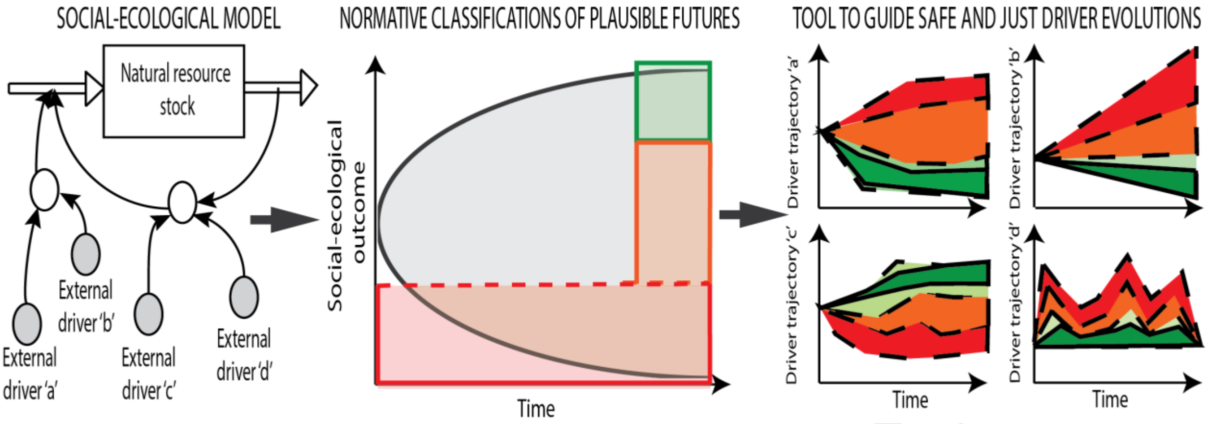
Tables

Table 1: Statistical outputs of the Kolmogorov-Smirnov test used to identify which drivers determine whether the model recreates Chilika's historical reference mode of growth, collapse and recovery (Fig. 3). Equations can be found in Appendix A. DO – dissolved oxygen; LMC – Lower Mahanadi catchment; R_c – rainfall-runoff coefficient; WC – Western catchments.

Significance level	p-value range	Driver name (K-S score)
1	$p < 0.01$	Sediment effect on aquatic vegetation growth (0.255); Ecological carrying capacity (0.252)
2	$0.01 \leq p \leq 0.1$	Fishers per boat (0.238); LMC sediment rate (0.238); WC R_c (0.191); Outlet closure (0.179)
3	$p > 0.1$	DO effect on aquatic vegetation growth (0.167); Salinity effect on aquatic vegetation growth (0.164); Fish natural deaths (0.163); Catch capacities (0.161); WC abstraction coefficient (0.150); Fecundity (0.145); WC evaporation coefficient (0.145); LMC evaporation coefficient (0.125); DO (0.119); Mature fish per KG (0.113); LMC abstraction coefficient (0.110); Littoral sediment (0.110); Salinity (0.110); LMC Rc (0.106); Days fished (0.102); WC sediment rate (0.102); Traditional upgrade (0.097); Reproductive life (0.077)

Table 2: The plausible trajectory ranges of the five external drivers used to generate the internal dynamics into future. See appendix C for graphical forms. Current rainfall and temperature values derive from the IPCC (2013) baseline period 1986-2005; current socioeconomic values are as of 2015.

System driver	**Current value (units)**	**Plausible change ranges**		
		Min	**Max**	**Rationale**
Annual average rainfall	1259.3 (mm/year)	0	+20% by 2065	RCP8.5 (IPCC, 2013)
Annual average temperature	25.3 (°C)	0	+3°C by 2065	RCP8.5 (IPCC, 2013)
Fish price	133.6 (INR/kg)	0	30 INR/kg/year	Maximum observed interannual increase (Appendix A1.1)
Diesel price	55.9 (INR/litre)	0	7 INR/litre/year	Maximum observed interannual increase (Appendix A1.1)
Birth rate minus death rate (Malthusian's 'r')	14.0 (dimensionless)	0	2.20%/year	Trajectory to double annual population by 2060



Graphical abstract

Highlights

1. The first *future* safe and just operating spaces of a real social-ecological system
2. Systems modelling explores resilience to driver interactions, feedbacks and management
3. Resilient causal pathways are traced back from pre-defined safe and just futures
4. Decommonisation extends Chilika's resilience to fishery intensification pathways
5. Decision-makers should target the "core space" of the safest driver interactions