Agent-based modelling to investigate angler behaviour in relation to management decisions and stock development.

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1.1 Summary

This Ph.D. project has two main aims. First, to enhance the understanding of angler behaviour and underlying decision mechanisms and second, to explore how agent-based models (ABMs) can be used to achieve this goal and to address methodological challenges from ABMs. The German recreational western Baltic cod fishery was used as a case study for recreational fisheries of social-ecological systems.

As a first step, major knowledge gaps regarding the modelling and understanding of angler behaviour were identified in recreational fisheries science, and it was shown that similar knowledge gaps exist in the case study fishery. The identified knowledge gap lies in the limited knowledge of anglers' decision-making mechanisms underlying and leading to behavioural changes, for example, as a response to management regulations. Behavioural changes were identified in the German recreational western Baltic cod fishery caused by the first-time introduction of a harvest restriction (hereafter referred to as bag limit) of 5 cod per angler and day. After the introduction of the bag limit, the recreational cod removals decreased more than expected, release rates increased, travel distances among charter boat anglers were reduced, and overall participation in the recreational cod fishery decreased. Furthermore, a shift in fishing effort away from months with a stricter bag limit of 2 cod per angler and day during the main spawning period was observed. Moreover, other management measures (bag limits, minimum landing sizes, slot limits, and seasonal closures) were also examined for their impacts on removals. The implications of these measures on fish populations and angler well-being in the case study fishery were discussed. Leading to the identification of a combination of different regulations that might represent a better management strategy. In addition, the data collection in the case study fishery was examined for possible biases in order to establish a trustworthy data basis.

As the next step, a structured review of ABMs in fisheries research was conducted, whereby the analytical framework was developed based on reviews of ABMs in various social-ecological system domains. It was shown that ABMs are used for a wide range of research purposes, including fisheries management guidance. Further, the reviewed ABMs modelled, for example, different management measures such as quotas or closed areas, as well as different decisions such as fishing effort, trip timing or the choice of fishing gear. These concepts and other approaches identified in the existing ABMs can be used as inspiration and starting points for future agent-based simulation studies and were also employed in this project. Challenges for ABMs in general and in fisheries science were identified. These challenges include 1) the limited representation of time in ABMs through fixed time intervals, frequently set at one day, 2) the prevailing utilisation of simplified decision mechanisms, often relying on maximisation routines, and 3) inadequate documentation of final ABMs coupled with the absence of documentation of the model development process and provenance attributes, resulting in diminished transparency and hindered reusability.

Subsequently, ABMs were developed to investigate the underlying decision mechanisms of anglers' behaviour, specifically focusing on angler site choices. It was uncovered how site choices were influenced by catches at different locations and travel distances, revealing that travel distances define spatial ranges within fishing locations are considered, while catch rates at different locations influence the final site choice. Furthermore, the Ph.D. project emphasises the importance of fishing methods in understanding angler behaviour. Different fishing methods showed various reactions to management regulations. For instance, bag limits impacted fishing methods with higher catch rates, such as sea-based cod fishing, stronger than fishing methods with lower catch rates, such as cod fishing from shore. The project also shows that angler heterogeneity contributes to different behavioural responses to regulations and, therefore, needs to be accounted for. Additionally, the ABMs identified differences in decision-making mechanisms between anglers executing different fishing methods. These differences encompass 1) different importance of travel distances and catch rates for the site choices and 2) differences in the suitability of decision theories to explain angler behaviour of anglers preferring different fishing methods.

An exploratory modelling approach combined with the "Keep it simple, stupid" (KISS) strategy was employed to address the challenges identified in the review. Starting with simple models, various model variations were developed and compared, delivering insides in angler decision-making and minimising

over-parametrization risks. Different decision theories, including "utility theory", "bandit problems", "explore-exploit-imitate", "prospect theory", and the "erotetic theory of decision" have been implemented in different models and variations. These theories are grounded in social science and partly include cognitive psychology principles like the influence of risks and reasoning. Therefore, they represent a more realistic representation of human decision-making mechanisms and thus address the challenge of simplified representations in most previous fisheries ABMs and ABMs in general. Additionally, different time representations and processing orders within ABMs were examined. Both discrete-events systems in continuous time and discrete time-stepped systems were implemented. The results demonstrate that time representation impacts vary based on the system's complexity and raise awareness to consider how time is represented in future simulation studies carefully. Different processing orders, i.e. synchronous and asynchronous, influenced even simple agent-based model outcomes, emphasising the importance of justifying and documenting the chosen processing orders for reliable and traceable model development. The model development process and the associated provenance information were publicly published using WebProv, and corresponding provenance graphics were created and presented. Thus, an application example of provenance approaches for agent-based modelling in fisheries science was created, which can be taken up by future simulation studies to overcome documentation challenges.
In the end, potential avenues for future research were pointed out. These encompass advancing location choice models towards reinforcement learning and including more factors into site choice models. Thereby, first application results and open questions in the developed reinforcement learning models were presented. The discussion also illustrated the utilisation of ABMs for modelling multi-day trip site choice and integrating various decision-making processes in recreational fisheries, proposing suitable decision theories for the decisions. Additionally, validation strategies for the developed models were discussed, and possible data sources for this process were identified. Moreover, the discussion highlighted potential applications of ABMs in fisheries management and the essential steps to enable their practical implementation.