`nash`: using Game Theory towards sustainable resource exploitation.

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Motivation

Our research aims to contribute towards the realisation of the 14th Sustainable Development Goal subscribed by the United Nations in the 2030 Agenda for Sustainable Development; particularly, on how to sustainably extract marine living resources through fishing (*1*).

Current management advice is provided on a *species-by-species* (SS) basis relative to the "Maximum Sustainable Yield" (MSY) target (*2*, *3*). Nonetheless, in marine systems species rarely (if at all) occur in isolation (*4*), sharing the factors that regulate their growth and (more often than not) feeding upon one another. Within this more realistic *multispecies* (MS) setting, applying SS-MSY based policies carries great risk of stock collapse (*5*).

In our research, we use abstract ecosystem models where trophic interactions are accounted for to obtain optimal harvesting rates for all exploited stocks in such a way that changes in any single rate cannot increase the long-term yield for that stock (*6*). This solution is by definition a *Nash Equilibrium* (NE) (*7*) in non-cooperative game theory where rational players maximise their benefits. In addition, we make our results better suited to inform managers.

Under the hood

We built an `R` package (*8*) called `nash` (*9*) that computes NE harvesting rates ($\mathbf{F}$) for ecological models of the form:

$$\frac{d\mathbf{B}}{dt} = \mathbf{f}(\mathbf{B}) \circ \mathbf{B} - \mathbf{F} \circ \mathbf{B}. \qquad (1)$$

The user defines an `R` function that contains equation (1) alongside an integration routine to solve it, taking $\mathbf{F}$ as input and returning long-term yields as output. The `nash` function will then approximate equation (1) near equilibrium dynamics by a multispecies Lotka-Volterra (LV) model, for which the NE can be computed analytically and so a first estimation of optimal $\mathbf{F}$ obtained. Subsequently, an updated LV approximation is calculated near the equilibrium given by this new $\mathbf{F}$. `nash` will then re-compute the NE starting a new iteration until a (user-adjustable) convergence threshold for $\mathbf{F}$ is reached.

The natural **solution** for optimal **harvesting** of **interacting** fish stocks is the **Nash equilibrium**. Our R package **nash** facilitates its computation for any arbitrary **user**-defined **ecosystem model**. Moreover, **realisability** of yield targets can be conveniently assessed by means of **Pareto frontiers**.

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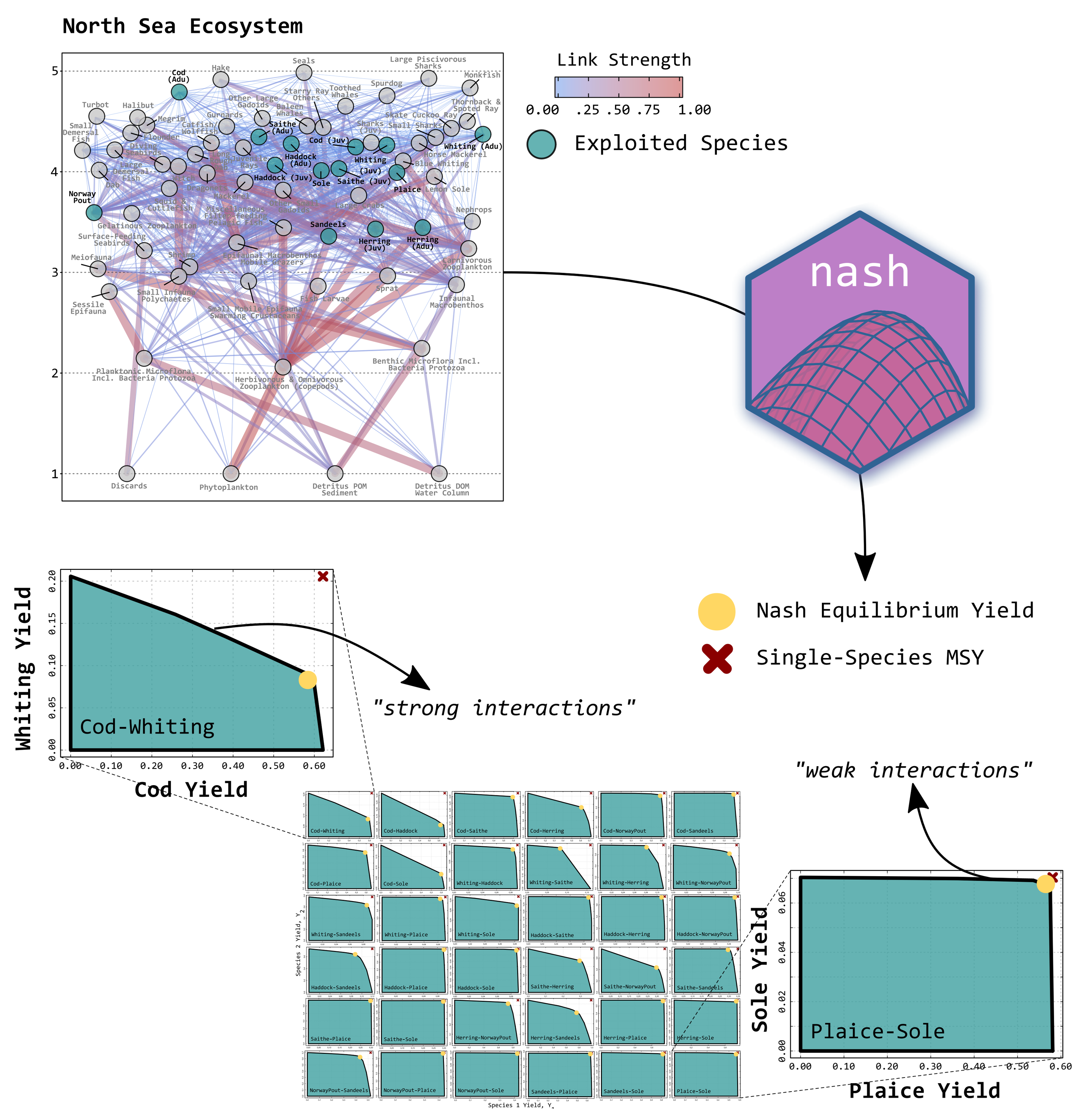
Results

Following (*10*) we explore all attainable yield combinations for nine commercial species in the North Sea Ecosystem for which their convex-hulls are plotted in a pairwise manner below. These areas are known as Pareto frontiers within which any management target is attainable (*e.g.* NE-MSY values ●). Furthermore, the shape of these areas facilitates pinpointing where true MS management advice is needed (*i.e.* a right-angled triangular shape ◺).



Conclusion

The SS-MSY targets (*i.e.* ✖ outside the blue areas) with which managers guide the North Sea fishing industry are unrealistic and will lead to stock collapse for most harvested species. By contrast, NE-MSY values live within these areas in all instances.

NE-MSY is conceptually the most intuitive analogue of SS-MSY given the existing European management framework easing the transition towards fully implementing ecosystem-based management policies globally.

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