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A case study of ecological suitability of mussel and seaweed cultivation using bivariate copula functions

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Aquaculture is gaining importance in the current context of continuous growth population as a source of (local) food resources and its potential of being combined with other uses at sea (e.g.: offshore energy production or tourism). Consequently, within the European Horizon 2020 project UNITED, the combination of mussel and seaweed cultivation together with wind energy production in the German North Sea is investigated. Here, the feasibility of the mussel **Mytilus edulis** and seaweed **Saccharina latissima** based on their ecological needs is analysed. Ecological data from a three-dimensional hydrodynamic and ecological model covering the northwest European continental shelf is used. For each of the two species, three variables are selected as relevant, including in both of them the water temperature. In addition, chlorophyll-a and dissolved oxygen are considered for mussels, and dissolved inorganic nitrogen and phosphorus are selected for seaweed. Temperature is selected as dominant variable so its daily maxima for the growing months are selected together with the concomitants of the other variables. Gaussian Mixture distributions (see McLachlan and Peel (2000)) and truncated Gaussian kernel distributions (see Bowman and Azzalini (1997)) are used to model the marginal distributions of the random variables. Bivariate copulas are fitted for each pair of variables to describe their dependence structure. Finally, probabilities of being within the optimal ranges of the relevant variables are calculated. Chlorophyll-a concentration and temperature are the most limiting variables for mussels and seaweed, respectively. Relatively low probabilities are obtained, since ranges for optimal growth are considered. Generally, it is feasible to cultivate mussels and seaweed at this location based on the selected ecological variables, as the probability of variables reaching values outside growth limits for the species is low.

Keywords: aquaculture, mussels, seaweed, feasibility, multi-use, marginal distribution, copulas, probability

1. Introduction

The continuous growth of the world's population is leading to challenges when looking for new sources of independent and green energy and (local) food sources. The marine space does bear a lot of potential to improve this situation, although the space is limited and the competition on sea is continually increasing. Ocean multi-use has arisen as a potential solution, since it allows to share and optimise the use of marine resources, infrastructures and space used by one or more activities. Possible uses of the oceans include wind energy production, aquaculture, or tourism. However, this field of multi-use at sea, especially when including aquaculture, is still very novel (Buck and Langan (2017), Buck et al. (2018)), so its exploitation comes with several risks and uncertainties.

The European Project UNITED (2020) aims to quantify and reduce those. The present study is focused on one of the five pilot studies included in such project. Here, the feasibility of cultivation of the blue mussel *Mytilus edulis* and seaweed (sugar kelp) *Saccharina latissima* is investigated at the Pilot FINO3 research platform of the project, located 80 km off the German coast. To do so, first, the relevant ecological variables for the aquaculture species, as well as their tolerability ranges, are identified. Later, these variables are modelled using a three-dimensional numerical model which covers the northwest European continental Shelf. Data on the daily extreme of the selected variables during the cultivation months are extracted from that model. Such data are used to build a dependence model using bivariate copulas between the selected variables and determine the probabilities to be within the tolerability ranges for cultivating mussel *Mytilus edulis* and seaweed *Saccharina latissima*. In this way, the suitability of aquaculture installations at this location is assessed.

2. Case Study

The FINO3 research platform is used as a case study. This location (with the coordinates 55.195° N, 7.1583° E) is indicated by a black star in Figure 1. The figure displays the water depth relative to Mean Sea Level (MSL) for the model domain. Note that logarithmic scale is used to properly display the depths in the shallow North Sea. The water depth at the research platform is about 20 m.

Due to its exposed position, the platform experiences harsh offshore conditions. Thus, a feasibility study (see Geisler et al. (2018)) was performed at this location to identify potential species which could grow and withstand those extreme hydrodynamic conditions. Two species were selected as mainly suitable to cultivate here: (1) the blue mussel *Mytilus edulis*, and (2) the seaweed *Saccharina latissima* (hereafter mussels and seaweed).

The aforementioned feasibility study also investigates the ecological variables which may influence the survival and growth of the species. Here, the most relevant variables are selected, and it is defined whether the maxima or minima of the variables is critical for the growth and survival of the mussels and seaweed. Since this study focused mainly on the hydrodynamic conditions which influence the survival and growth rate of the species, hydrodynamic variables are disregarded here, and only ecological variables are considered. The selected variables are:

Water Temperature T_w $[°C]$

Easy to measure magnitude, which is one of the most relevant variables influencing the growth of the species. Also, T_w highly influences other variables, so it is selected as the dominant variable. Mussels are relatively resistant to extreme water temperatures (high and low), while seaweed can die from 21 $°C$. However, here the optimal T_w ranges for each species are considered and displayed in Table 1 (Fly and Hilbish (2013) and Buck (2002)).

Dissolved Oxygen O_{diss} $[g/m^3]$

The minimum oxygen concentration highly influences the mussels survival, while it is irrelevant

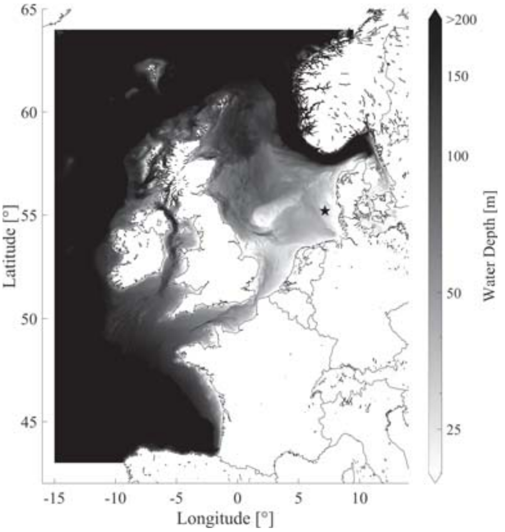

Fig. 1. Map of the European shelf representing the model domain and displaying the water depth relative to MSL (in logarithmic scale). The location for the present case study, FINO3 research platform, is marked by a black star.

for seaweed. Lower limit for mussels is 2 g/m^3. [Tyler-Walters and Hiscock (2008), Tang and Riisgård (2018)].

Nutrients DIN $[g/m^3]$ **and** DIP $[g/m^3]$
The main nutrients in sea water relevant for the seaweed are dissolved inorganic nitrogen, DIN, (ammonium and nitrate) and dissolved inorganic phosphorus, DIP, (phosphate) (Buck and Buchholz (2004)). Nutrient concentrations are dependent on the water temperature T_w,and thus vary between seasons. The minima of these three variables are selected to be critical for the seaweed, while the variables are rather irrelevant for the mussels. The selected limits according to Broch and Slagstad (2012) and Lubsch and Timmermans (2019) are shown in Table 1.

Chlorophyll-a Chl_a $[mg/m^3]$
Similar to nutrients, the Chl_a concentration is highly influenced by the water temperature T_w. For mussels, the optimal ranges are determined from 6.3 till 10 mg/m^3 chlorophyll-a (Riisgård et al. (2011)), while for seaweed, it is irrelevant.

Table 1. Overview of variables affecting growth for the mussels Mytilus edulis and seaweed Saccharina latissima, as well as their critical limits at the location of the FINO3 research platform.

Variable	Limits/ranges:	
	Mussels	Seaweed
T_w $[°C]$	10 - 20	10 - 17
O_{diss} $[g/m^3]$	> 2	-
Chl_a $[mg/m^3]$	6.3 - 10	-
DIN $[g/m^3]$	-	$>$ 0.056
DIP $[g/m^3]$	-	$<$ 0.093

It should be noted that the depths of the longlines for the mussel and seaweed cultivation should be between 7 to 11 m (9 m are selected here), and 0 to 4 m below MSL (2 m are selected), respectively. Additionally, the growth period for the species differs: for it is between March and October, for the seaweed it is September until May.

3. Methodology

Data is obtained from simulations performed using a three-dimensional hydraulic and ecological model, which makes use of the software D-Flow Flexible Mesh. Two years of model output are used (2014 and 2015) to sample daily maxima of water temperature for the relevant seasons (see Table 1). As the temperature is relevant for both species, it can be seen as the main driver for other variables. Concomitants (minima) of the other variables are taken. Marginal distribution functions are fitted to each random variable using the sampled values and their goodness of fit (GOF) is assessed using Akaike Information Criterion (AIC) (Akaike (1974)). Next, bivariate copulas are used to model the dependence between each pair of random variables. The normal (Gaussian) and three Archimedean copulas (Gumbel, Clayton, Frank) are considered. These are considered because of their familiarity and because they model the ranges of asymmetries usually observed in applications (lower and upper tail dependence). In the end, probabilities are computed for relevant cases at the location of interest.

3.1. *Hydrodynamic and ecological numerical model*

Hydrodynamic and ecological variables are modelled using a three-dimensional hydrodynamic model called the 3D Dutch Continental Shelf Model (3D DCSM-FM, see Zijl et al. (2021)) using the the software D-Flow Flexible Mesh. The model domain covers the Northwest European Continental Shelf from 15° W to 13° E and from 43° N to 64° N (in geographical coordinates) including both deep oceanic and shallow coastal waters, as displayed in Figure 1. A flexible mesh is used, the grid resolution is spatially variable with coarse resolution in deep waters, which increases towards shallow waters. To allow a high vertical resolution across all depths, two types of layers are combined as a vertical grid. One type is characterized by a fixed number of layers, which leads to a high resolution in shallow waters. In order to represent the deep waters in a high resolution as well, layers with a fixed thickness are used below the near-surface thickness-varying layers. The horizontal grid cells between changing resolutions across the domain are connected via triangles. In total, approximately 630,000 cells are used. The

3D DCSM-FM model is forced with ERA5 meteorology data at the atmospheric boundary [Hersbach et al. (2018)]. The model is validated for the period of 2013-2017 (see Zijl et al. (2021)). For this study, the hydrodynamic D-FLOW FM model is run integrating the D-Water Quality module to provide information about ecological variables (see Lenhart et al. (2022)). It should be noted that phosphorus may be underestimated by the numerical model.

3.2. *Marginal distributions*

Each random variable is fitted to a Gaussian Mixture distribution with 2 up to 5 components. The best fitting Gaussian Mixture according to Akaike Information Criterion (AIC) will be selected. In case the Gaussian Mixture distributions do not lead to a satisfactory fit, a non-parametric Gaussian kernel distribution is used. This kernel function is truncated to positive values. The “Statistics and Machine Learning Toolbox” version 12.2 (MathWorks (2022)) from the software MATLAB is used here for both the univariate distributions and the copula models.

3.3. *Copula model*

As previously mentioned, bivariate copulas are used to describe the dependence between variables. Copulas are joint multivariate distributions with uniform marginal distributions in [0,1]. Bivariate copulas are defined as

$$H(x, y) = C(F(x), G(y)) \tag{1}$$

where $H(x, y)$ for $(x, y) \in \mathbb{R}^2$ is a joint distribution with marginals $F(x)$ and $G(y)$ and C is a copula in the unit square $I^2 = ([0, 1] \times [0, 1])$. Eq. (1) is satisfied for all $(x, y) \in \mathbb{R}^2$ (Joe (2015)).

Many copula models exist. Here, the following four copula models are considered: the Gaussian (normal) copula and three copulas from the Archimedean family (Gumbel, Clayton and Frank). These four copula models are fitted for each pair of studied random variables and the best model representing the data is selected based on two goodness of fit measures. The first one is Cramer-von-Mises statistic (CvM), described in Genest et al. (2009), which is based on the distance between the empirical joint cumulative distribution function (ecdf) and the parametric joint cumulative distribution function given by the copula model. Thus, the lower the CvM, the better. For the calculation of the CvM statistic, the BANSHEE toolbox version 1.3 is used (see Paprotny et al. (2020) and for a Python implementation see Koot et al. (2023)). The second technique used here are the semi- (or quasi-) correlations described in Joe (2015). This technique can be used not only to assess the goodness of fit of a copula but also to evaluate if asymmetries such as tail dependence are captured by the copula model. In case the results of the goodness of fit techniques do not align, the results of the CvM are followed.

3.4. *Calculation of probabilities*

Using the described dependence model, exceedance or non-exceedance probabilities (or any other probability of interest) of the studied variables can be calculated. Note that limits for optimal growth of the species are given in Table 1. Here, the probabilities of being within the ranges of optimal growth are calculated via Monte Carlo simulations.

4. Results

As described in Section 3, daily maxima values of T_w are sampled together with the concomitant values (minima) of the remaining variables from the model data (see Table 1). In Figure 2, the sampled data for mussels are displayed. Figure 3 shows the scatter matrix for the seaweed.

4.1. *Correlation Analysis*

Spearman’s rank correlation coefficient (r) are calculated as a starting point of the dependence analysis between the selected random variables (see Table 2). It assesses the degree of dependence between the random variables. $r \in [-1, 1]$, where r = 1 and -1 represent the perfect (monotonic) positive and negative correlation, respectively. It is given by

$$r = \frac{Cov[R(X), R(Y)]}{\sigma_{R(X)}\sigma_{R(Y)}} \tag{2}$$

where $Cov[R(X), R(Y)]$ is the covariance of the ranked variates, and $\sigma_{R(X)}$ and $\sigma_{R(Y)}$ are the stan-

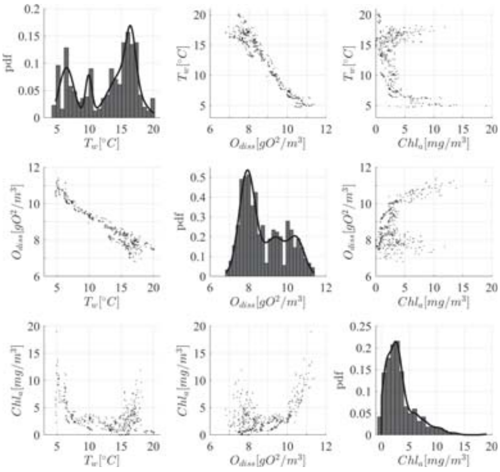

Fig. 2. Overview of sampled data for mussel cultivation case: daily maximum T_w and concomitants for minimum O_{diss} and Chl_a. The univariate histograms with fitted pdfs are displayed on the diagonal

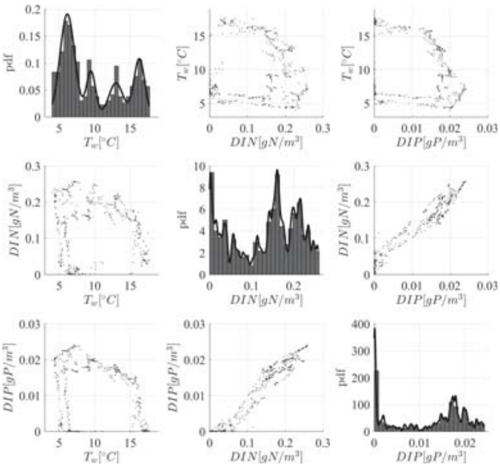

Fig. 3. Overview of sampled data for seaweed cultivation case: daily maximum T_w and concomitants of minimum DIN and DIP. The univariate histograms with fitted pdf are displayed on the diagonal

dard deviations of the same variates. Additionally, the p-values are calculated to determine the significance of the observed correlations. P-values below the significant level ($\alpha = 0.05$) indicate that the observed correlation is significantly different from zero, which is the case for all variable pairs studied here, except for T_w and DIN ($\alpha = 0.14$).

Table 2. Spearman rank correlations between relevant variables for mussels and seaweed.

Mussels			
	T_w	O_{diss}	Chl_a
T_w	1	-0.93	-0.31
O_{diss}		1	0.38
Chl_a			1
Seaweed			
	T_w	DIN	DIP
T_w	1	-0.07	-0.21
DIN		1	0.95
DIP			1

4.2. *Marginal distributions*

Univariate marginal distribution functions are fitted to the previously described variables (see Figures 2 and 3). The Gaussian Mixture distribution is selected considering from 2 to 5 components. The optimal number of components is selected based on the Akaike Information Criterion (AIC). Akaike Information Criterion accounts for both the goodness of fit and the number of parameters and is defined as

$$AIC = 2k - 2ln(\hat{L}) \tag{3}$$

where k is the number of estimated parameters and $\hat{L}$ is the maximized value of the likelihood function. For 3 out of 6 variables, the Gaussian Mixture distribution provides a good fit. A summary of the results is shown in Table 3. For the missing variables, a nonparametric truncated Gaussian kernel distribution was applied.

4.3. *Copula model fitting*

The best fitting copula model is defined according to CvM statistic and semi-correlations as exposed in Section 3.3. As an example of such process, detailed results for the pair T_w and O_{diss} for mussels are presented in Figure 4 and Tables 4 for the CvM statistic results and 5 for the semi-correlation results. Note that the smaller the CvM statistic, the better the fit. Very similar results are shown for Frank and Clayton copula.

Regarding the results of semi-correlations (see Table 5), the correlation for the empirical data set is much larger in the north-west quarter than in the south east, which indicates a tail dependence. As the Gaussian and Frank copula are symmetric

Table 3. Summary of fitted Gaussian Mixture distributions, where μ and σ represent the mean and standard deviation of each component and CP shows the component proportions.

	Parameter	
	Tw	Oxy
	Mussels	
μ	[9.32 6.08; 16.46; 15.46]	[7.93; 10.52; 9.39]
σ	[2.31; 0.79; 0.55; 4.50]	[0.18; 0.16; 0.34]
CP	[0.17; 0.20; 0.17; 10.46]	[0.55; 0.17; 0.28]
	Seaweed	
μ	[6.15; 16.29; 9.47; 12.99]	-
σ	[1.08; 0.57; 0.39; 1.13]	-
CP	[0.50; 0.20; 0.13; 0.16]	-

Table 4. Cramer-von-Mises goodness of fit results for the pair T_w with O_{diss}.

	Copula parameter	CvM Statistic
Gaussian	-0.873	0.593
Gumbel	2.599	1.143
Clayton	4.841	0.201
Frank	-15.172	0.252

(no tail dependence), Clayton copula seems to better represent the dependence structure between the variables, as also indicated by CvM statistic. Note that in case of misalignment between both goodness of fit tests, best model according to CvM statistic are adopted.

Table 5. Semi-correlations for the empirical and fitted copula functions for the pair T_w with O_{diss}.

	r se	r nw
Empirical	-0.371	-0.880
Gaussian	-0.734	-0.706
Gumbel	-0.783	-0.520
Clayton	-0.216	-0.830
Frank	-0.692	-0.701

The fitted copula models for T_w and O_{diss} are shown in Figure 4 for the Gaussian, Gumbel, Clayton and Frank copula.

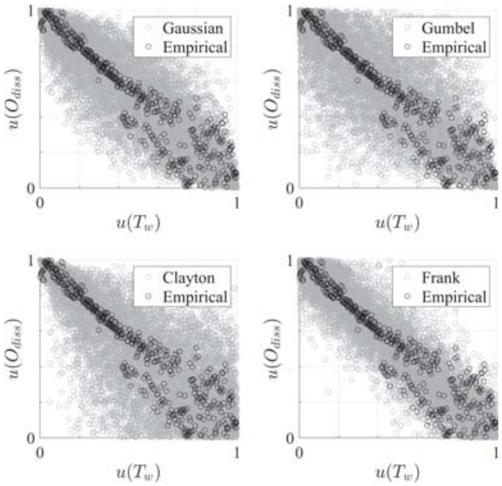

Fig. 4. Empirical copula against fitted Gaussian, Gumbel, Clayton and Frank copulas for the pair T_w and O_{diss}

In Table 6, a summary of the best fitting copulas for each pair of variables is given. Tail dependence seems to be relevant for the random variables in the mussels case, since Clayton copula is selected in two up to three bivariate pairs. Regarding the seaweed case, tail dependence does not seem to be relevant, since Gaussian and Frank copulas are found as the best models.

Table 6. Overview of the of best fitting bivariate copulas and its parameters for each pair of variables.

Variable Pair	Copula	Parameter
	Mussels	
T_w - O_{diss}	Clayton	4.841
T_w - Chl_a	Clayton	0.723
O_{diss} - Chl_a	Gaussian	0.433
	Seaweed	
T_w - DIN	Gaussian	-0.123
T_w - DIP	Gaussian	-0.251
DIN - DIP	Frank	18.247

4.4. *Calculation of probabilities*

Here, probabilities of being within the desired ranges for cultivating mussels and seaweed are calculated (see Table 1). Therefore, Monte Carlo simulations are performed; 10,000 random samples are generated via the selected copulas and probabilities are calculated. The results are shown in Table 7.

Table 7. Results of the probabilities of fulfilling the conditions defined in Table 1.

Mussels			
	T_w	O_{diss}	Chl_a
T_w	0.675	0.673	0.024
O_{diss}		0.998	0.108
Chl_a			0.111
Seaweed			
	T_w	DIN	DIP
T_w	0.359	0.262	0.360
DIN		0.761	0.762
DIP			0.998

Regarding the mussels, the joint probability of T_w being in the optimal range and O_{diss} being above the minimum ensuring their survival is about 67 %. This is mainly limited by the optimal range of T_w. The most limiting variable is Chl_a, since the probability of reaching the optimal values is roughly above 10 %. Consequently, the joint probabilities with T_w or O_{diss} limits, lead to very small probabilities. Note that for the relevant months, increased T_w usually occurs together with decreased Chl_a. Additionally, for T_w and Chl_a, ranges are selected for optimal growth conditions, while for O_{diss} critical limits are selected. With regard to seaweed, the most limiting variable is T_w (see Table 1). The most unfavourable case is the joint probability of DIN and T_w reaching most favourable values which decreases until 26 %. The seaweed still grows at water temperatures below 10 $^\circ C$ while temperatures above 20 $^\circ C$ are lethal. Note that for DIN and DIP absolute limits are respected.

5. Conclusions

The aim of this study was to assess the suitability of cultivation of mussel *Mytilus edulis* and seaweed *Saccharina latissima* at the location of the FINO3 research platform in the North Sea. This was done by calculating the probabilities of having the relevant ecological variables within their optimal ranges (see Table 1). To this end, data on those ecological variables from a numerical model was used. First, relevant variables were selected for each species and extracted from the model. Second, the dominant variable for both species was identified: water temperature. Thus, its daily maxima during the growing period of each species was sampled together with the concomitants of the other relevant variables. A probabilistic model was then built based on the sampled data; dependence structure was modelled using bivariate copulas while the univariate distribution of each random variable was modelled using a Gaussian Mixture or a non-parametric truncated Gaussian kernel distribution. Probabilities were calculated using Monte Carlo simulations and shown in Table 7.

From the calculated probabilities, chlorophyll-a was found to be the most limiting variable for mussels due to a rather small range of optimal concentrations, which is mainly reached during bloom event in spring. During the summer, the concentrations drop below the optimal range, although the observed concentrations still enable mussels to grow. Regarding the seaweed, temperature was the most limiting variable. However, it should be noted that this species still grows at water temperatures below the optimal range, while higher temperatures can lead to the death of the seaweed. Thus, the lower limit of temperature could be revisited to account for this. Different to the water temperature, the probability of nutrients being above or below the limits, respectively, is comparably high.

Concluding, based on the ecological variables investigated for seaweed *Saccharina latissima* and mussel *Mytilus edulis*, it seems feasible to grow these species at this offshore location in the North Sea. Even though the probability of the variables being in the range for optimal growth conditions is rather low (11 to maximum 68 % for chlorophyll-a and temperature), the set limits for the other variables for the growth period for both species is high (76 % for DIN to 99.9 % for dissolved oxygen and DIP, respectively). Thus, the actual feasibility probability is higher than that calculated.

Future work will focus on improving the feasibility calculations by independently accounting for: (1) ranges for survival of the species and (2) ranges for optimal growth conditions. In this manner, it will be considered not only the survival of mussels and seaweed but also the productivity of such aquaculture products. In addition, this study will be extended from one location to the whole southeastern North Sea to account for spatial differences between the relevant variables. In this way, feasibility maps will be provided to identify the optimal investment locations.

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