

# Quantitative mapping and predictive modelling of Mn-nodules' distribution from hydroacoustic and optical AUV data linked by Random Forests machine learning.

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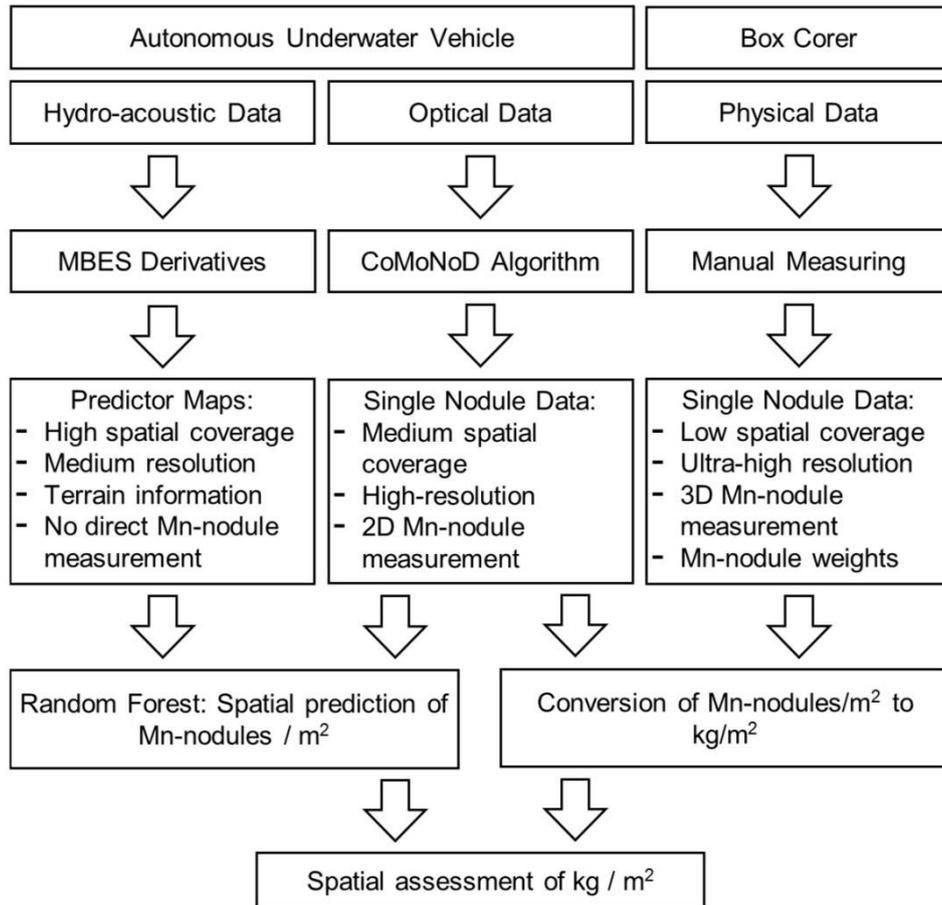
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**Abstract.** In this study, high-resolution bathymetric multibeam and optical image data, both obtained within the Belgian manganese (Mn) nodule mining license area by the autonomous underwater vehicle (AUV) Abyss, were combined in order to create a predictive Random Forests (RF) machine learning model. AUV bathymetry reveals small-scale terrain variations, allowing slope estimations and calculation of bathymetric derivatives such as slope, curvature, and ruggedness. Optical AUV  
15 imagery provides quantitative information regarding the distribution (number and median size) of Mn-nodules. Within the area considered in this study, Mn-nodules show a heterogeneous and spatially clustered pattern and their number per square meter is negatively correlated with their median size. A prediction of the number of Mn-nodules was achieved by combining information derived from the acoustic and optical data using a RF model. This model was tuned by examining the influence of the training set size, the number of growing trees (*ntree*) and the number of predictor variables to be randomly selected at  
20 each RF node (*mtry*) on the RF prediction accuracy. The use of larger training data sets with higher *ntree* and *mtry* values increases the accuracy. To estimate the Mn-nodule abundance, these predictions were linked to **ground-truth** data acquired by box coring. Linking optical and **hydroacoustic** data revealed a non-linear relationship between the Mn-nodule distribution and topographic characteristics. This highlights the importance of a detailed terrain reconstruction for a predictive modelling of Mn-nodule abundance. In addition, this study underlines the necessity of a sufficient spatial distribution of the optical data  
25 to provide reliable modelling input for the RF.

## 1. Introduction

High-resolution quantitative predictive mapping of the distribution and abundance of manganese nodules (Mn-nodules) is of interest for both the deep-sea mining industry and scientific fields as marine geology, geochemistry, and ecology. The distribution and abundance of Mn-nodules are affected by several factors such as local bathymetry (Craig 1979; Kodagali, 1988; Kodagali and Sudhakarand, 1993; Sharma and Kodagali, 1993), sedimentation rate (Glasby, 1976; Frazer and Fisk, 1981; von Stackelberg and Beiersdorf 1991; Skornyakova and Murdmaa, 1992), availability of nucleus material (Glasby, 1973), and bottom current strength (Frazer and Fisk, 1981; Skornyakova and Murdmaa, 1992). As a consequence, the distribution and abundance of Mn-nodules is heterogeneous (Craig, 1979; Frazer and Fisk, 1981; Kodagali, 1988; Kodagali and Sudhakar, 1993; Kodagali and Chakraborty, 1999; Kuhn et al., 2011), even on fine scales of 10 to 1,000 m (Peukert et al., 2018a; Alevizos et al., 2018). This increases the difficulty for quantitative predictive mapping using remote sensing methods. Vast areas of the seafloor can be mapped by ship-mounted, multibeam echo-sounder systems (MBES). State-of-the-art MBES systems feature a low frequency (12 kHz) and can map ca. 300 km<sup>2</sup> of seafloor in 4,500 m water depth per hour. Hence, low-resolution regional maps can be created at a grid cell size of 50 to 100 m within which the main Mn-nodule occurrence can become apparent, based on the backscatter intensity (Kuhn et al., 2011; Rühlemann et al., 2011; Jung et al., 2001). A general separation in areas of high and low abundance (kg/m<sup>2</sup>) of Mn-nodules seems possible, especially in flat areas where sedimentological changes and physical influences on the footprint size and incidence angle of the transmitted acoustic pressure wave can be corrected accurately (De Moustier, 1986; Kodagali and Chakraborty, 1999; Chakraborty and Kodagali, 2004; Kuhn et al., 2010 and 2011, Rühlemann et al., 2011 and 2013). However, the patchy distribution of Mn-nodules in size and number at meter-scale cannot be resolved with ship-mounted MBES data (Petersen, 2017). For an operational resource assessment, a higher resolution of few meters grid cell size is needed to supply accurate depth, slope, and Mn-nodule distribution variability (Kuhn et al., 2011). Supplementary to the spatial mapping by acoustic sensors, point-based measurements from box-corer samples are used as ground-truth data for training and validation of geostatistical techniques (e.g. kriging) in order to create quantitative maps of Mn-nodule abundance (Mucha et al., 2013; Rahn, 2017). However, the generally low number of ground-truth samples during surveys (usually below 10), their limited sampling area (typically 0.25 m<sup>2</sup>) and the relatively large distance between them (> 1 nmi) prevent an accurate correlation with the ship-based MBES data and thus a good prediction of the total Mn-nodules' mass and distribution in large areas (Petersen, 2017). Importantly, the sparse sampling with box corers affects the performance of interpolation and geostatistical techniques, which are typically applied during data analysis (Li and Heap, 2011 & 2014; Kuhn et al., 2016). In this article, we address this challenge by combining high-resolution hydroacoustic and optical data sets acquired with an Autonomous Underwater Vehicle (AUV) and connecting those data with a Machine Learning (ML) algorithm (here Random Forests), in order to predict the spatial distribution of the number of Mn-nodules per square meter. Unlike geostatistical methods, ML can be used to incorporate information from different bathymetric derivative layers and to detect complex relationships among predictor variables without making any prior assumptions about the type of their relationship or value distribution (Garzón et al., 2006;

Lary et al., 2016). To this direction, first predictions have already been achieved (Knobloch et al. 2017; Vishnu et al., 2017; Alevizos et al., 2018). Here, we present a complete data analysis workflow for potential mining operations (Figure 1).



65 **Figure 1.** Schematic workflow of the data sets used in this study to enable the spatial assessment of Mn-nodules inside the study area. The medium resolution of AUV MBES (m scale) is referring to the comparison of the optical and physical data (cm scale).

### 1.1 AUV hydroacoustic mapping

70 AUVs have proven their usefulness for multibeam data acquisition in the deep-sea environment (Grasmueck et al., 2006; Deschamps et al., 2007; Haase et al., 2009; Wynn et al., 2014; Clague et al., 2014 and 2018; Pierdomenico et al., 2015; Peukert et al., 2018a). They achieve higher spatial and vertical resolution compared to ship-mounted MBESs. This is due to their operation close to the seafloor which results in a smaller footprint at a given beam angle and enables the use of higher frequencies (Henthorn et al., 2006; Mayer, 2006; Caress et al., 2008; Paduan et al., 2009). Additionally, AUVs avoid

75 problems like near-surface turbulences, bubbles, ship-noise and strong sound velocity changes (Kleinrock et al., 1992a and  
1992b; Jakobson et al., 2016; Paul et al., 2016). They work independently from the surface vessel and operate at a stable  
altitude. AUVs can efficiently conduct a dive pattern of dense survey lines and thus reduce survey effort and costs (Chance  
et al., 2000; Bellingham, 2001; Bingham et al., 2002; Danson, 2003; Roman and Mather, 2010). High-resolution bathymetry  
enables computing bathymetric derivatives like slope and rugosity with a similarly high resolution. These derivatives play an  
important role in predicting Mn-nodules' distribution and abundance (Craig, 1979; Kodagali, 1988; Skornyakova and  
80 Murdmaa, 1992; Kodagali and Sudhakar, 1993, Sharma & Kodagali, 1993; Ko et al., 2006). However, a small number of  
recent studies have investigated this role in an AUV scale (Okazaki and Tsune, 2013; Peukert et al., 2018a; Alevizos et al.,  
2018).

### 1.2 Underwater optical data

Underwater optical data have generally played an important role in the qualitative analysis of the seafloor features and for  
85 the specific task of assessing Mn-nodules' distribution explicitly (Glasby, 1973; Rogers, 1987; Skornyakova and Murdmaa,  
1992; Sharma et al., 1993). The development of automated detection algorithms enabled quantitative optical image data  
analysis and subsequent statistical interpretation of Mn-nodule densities. The spatial coverage of optical imaging is much  
higher than for box core sampling. The data resolution remains high enough to reveal the high variance in the spatial  
distribution of nodules at meter scale. Thus optical data can fill the investigation gap between ground-truth sampling and  
90 hydroacoustic remote sensing (Sharma et al., 2010 and 2013; Schoening et al., 2012a, 2014, 2015, 2016 and 2017a; Kuhn  
and Rathke, 2017). Moreover, mosaicking of optical data could reveal mining obstacles such as outcropping basements or  
volcanic pillow lava flows. In addition, seafloor photos are the source for evaluating benthic fauna occurrences and related  
habitats on a wider area (Schoening et al., 2012b; Durden et al., 2016).

### 1.3 Box corer sampling

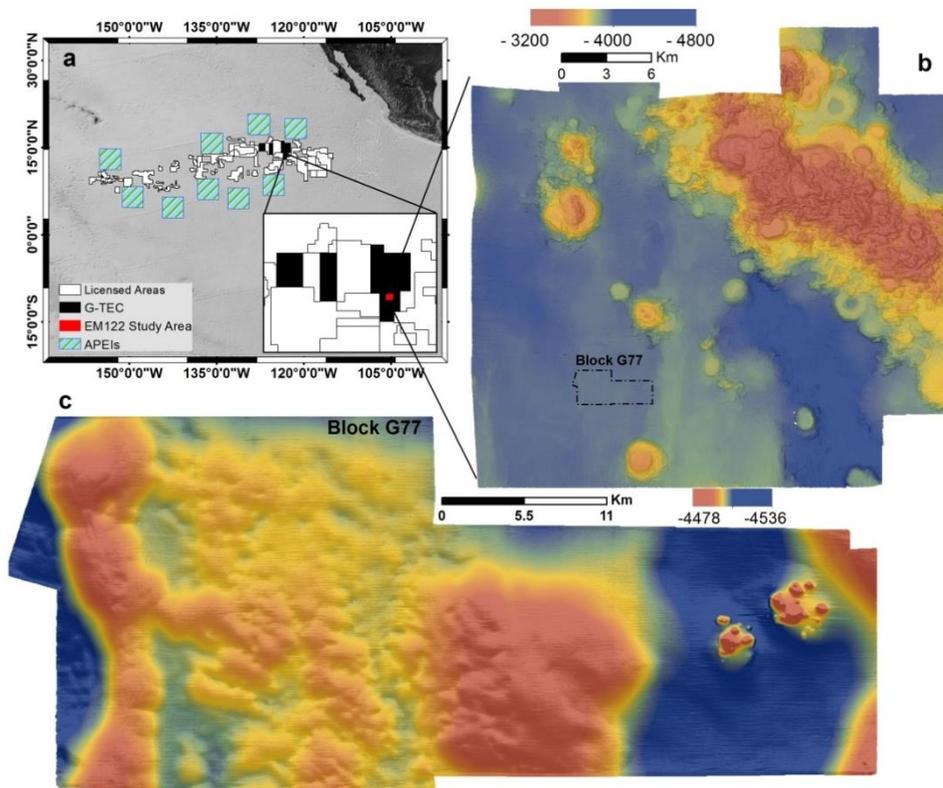
95 Box coring is common to obtain physical samples of Mn-nodules and sediments for resource assessments and biological  
studies. While optical data reveal only the exposed and semi-buried Mn-nodules, box corers collect the top 30-50 cm of the  
seafloor with minimum disturbance, allowing an accurate measure of the Mn-nodules' abundance ( $\text{kg/m}^2$ ). Box coring data  
are used for training and validation in geostatistical methods for quantitative and spatial predictions of Mn-nodules (e.g.  
Mucha et al., 2013; Knobloch et al., 2017). The representativeness of box coring data is disputable as few deployments can  
100 be made due to time constraints (ca. 4h per core) and as the spatial coverage of one sample is rather low (ca.  $0.25 \text{ m}^2$ ).

## 1.4 Random Forests

Random Forests (RF) is an ensemble machine learning (ML) method composed of multiple weaker learners, namely classification or regression trees (Breiman, 2001a). Within RF an ensemble of distinct tree models is trained using a random subsample of the training data for each tree until a maximum tree size is reached. In each tree, each node is split using the best among a subset of predictors randomly chosen at that node instead of using the best split among all variables (Liaw & Wiener, 2002). Thus, the process is double-randomized which further reduces the correlation between trees. About two thirds of the training data are used to tune the RF while the remaining ‘out-of-bag’ (OOB) samples are used for an internal validation. By aggregating the predictions of all trees (majority votes for classification, the average for regression) new values can be predicted. This aggregation keeps the bias low while it reduces the variance, resulting in a more powerful and accurate model. RFs have the ability to estimate the importance of each predictor variable which enables data mining of the high-dimensional prediction data. Terrestrial studies use RFs in prospectivity mapping of mineral deposits (Carranza and Laborte, 2015a; 2015b; 2016; Rodriguez-Galiano et al., 2014 and 2015). In the marine environment, RFs have been used to combine MBES bathymetry, backscatter, their derivatives, sediment sampling, and optical data for various seabed classification and regression tasks (e.g. Li et al., 2010; Li et al., 2011a; Che Hasan et al., 2014; Huang et al., 2014). Further studies showed the robustness of RFs for selected data sets compared to other ML algorithms (Che Hasan et al., 2012; Stephens and Diesing, 2014; Diesing and Stephens, 2015; Herkul et al. 2017), as well as to geostatistical and deterministic interpolation methods (Li et al., 2010, 2011b and 2011b; Diesing et al., 2014).

## 2. Study Area

The study area lies in the Clarion–Clipperton Zone (CCZ; ca.  $4 \times 10^6$  km<sup>2</sup>) in the Eastern Central Pacific Ocean. The CCZ triggered scientific and industrial interest for several decades due to its high resource potential in Mn-nodules deposits (Hein et al., 2013; Petersen et. al., 2016) with an average nodule abundance of 15 kg/m<sup>2</sup> (SPC, 2013). At the time of writing, the International Seabed Authority (ISA) has granted 17 exploration licences inside the CCZ (Figure 2a). The study area described here is part of the Belgian GSR license area (Figure 2b) and will be referred to as Block G77 (Figure 2c). Overall, this part of the Belgian license area has high bathymetric range, and complex morphology, due to the presence of submarine volcanoes, solitary seamounts and seamount chains. Block G77 is characterized by a low bathymetric range (77 m) and mostly gentle slopes (95% of the area below 5°). An exception is located in the eastern part, where sub-recent small-scale volcanic activity created 15 cone-shaped morphological features of up to 55m height and 150m width that are clustered in an area of ca. 700 m x 380 m. Despite the gentle slopes, block G77 is characterized by an uneven micro-relief (according to Dikau **scale** (1990)) especially in the western part, where small (2-4 m) depressions coexist next to short (2-4 m) protrusions. In the central part, a 30 m high elevation acts as a natural barrier between the western part of the study area that features more relief and the eastern part that is deeper **and** has less relief (Figure 2c).



**Figure 2.** a) Areas of Particular Environmental Interest (APEIs), licensed areas (white) and the Belgium / GSR licenses area (black) within the CCZ. b) Regional bathymetric map of the study area, created by the EM 122 MBES on R/V SONNE (cruise SO239). c) Block G77, mapped by AUV Abyss with a Teledyne Reson Seabat 7125 MBES.

### 3. Methodology

#### 3.1 Hydroacoustic Data Acquisition & Post Processing

The data (Greinert, 2016) were collected in March 2015 during cruise SO239 EcoResponse (Martínez Arbizu & Haeckel, 2015) with the German Research Vessel Sonne. Ship-based mapping was conducted with a hull-mounted Kongsberg EM 122 MBES (12 kHz, 0.5° along- and 1° across-track beam angle, 432 beams with 120° swath angle). High-resolution MBES data were acquired with AUV Abyss (GEOMAR, 2016) inside Block G77 equipped with a Teledyne Reson Seabat 7125 MBES (200 kHz, 2° along- and 1° across-track beam angle, 256 beams with 130° swath angle). The data (60 km of survey lines) were acquired from 50m altitude and with 100% swath overlap resulting in an insonification of 9.5 km<sup>2</sup>. Post-processing of the AUV data was conducted with the Teledyne PDS2000 software for data conversion of the raw data into s7k and GSF format. Further multibeam processing (sound velocity calibration, pitch/roll/yaw/latency artifacts correction) was performed using the Qimera™ software. The largest uncertainties during AUV operations result from inaccurate

navigation and localization in the deep-sea environment (Paull et al., 2014). AUV Abyss has a combination of five different systems for navigation and positioning: Global Positioning System (GPS) when at the sea surface, Doppler Velocity Log (DVL) when 100 m or less from the ground, Inertial Navigation System (INS), Long Baseline Acoustic Navigation (LBL) and dead reckoning (GEOMAR, 2016). Each system has its own limitations that contribute to the total navigation error (Sibenac et al., 2004; Chen et al., 2013) that generally results in positioning drifts over time. Consequently, this affects the position accuracy of the MBES and photo data. Our AUV MBES data processing and an absolute geo-referencing of the resulting AUV-bathymetry grid with the EM122 ship data, supplemented with the use of mbnavadjust in MB-Systems, (Caress et al, 2017) resulted in a well calibrated AUV bathymetric dataset. The position of the AUV image data ‘only’ relies on the above mentioned sensors with a not quantifiable ‘small’ position error. Backscatter data were excluded from the modelling procedure due to artifacts and a general poor quality. The output grid cell size for the analyses was set to 3 m x 3 m. The depth raster was exported as ASCII format for further analysis in SAGA GIS v.6.3.0. SAGA includes numerous tools that focus on DEM and Terrain Analysis (Conrad, 2015). Eight bathymetric derivatives were computed (Table 1) with the SAGA algorithms (Appendix A).

**Table 1.** The bathymetric derivatives computed in SAGA GIS and used as predictor variables.

Derivative	Description
Slope (S)	The first derivative of the bathymetry and describes the steepness of a surface.
Plan Curvature (Pl.C)	The second derivative of the bathymetry and perpendicular to the direction of the maximum slope (Zevenbergen and Thorne, 1987).
Profile Curvature (Pr.C)	The second derivative of the bathymetry and parallel to the direction of the maximum slope (Zevenbergen and Thorne, 1987).
Topographic Position Index (TPI)	Compares the elevation of a single pixel to the average of multiple cells surrounding it in a defined distance (Weiss, 2001).
Broad-scale (TPI_B)	Distance: 150-400 m
Medium-scale (TPI_M)	Distance: 50-150 m
Fine-scale (TPI_F)	Distance: 0-50 m
Concavity (C)	In each cell its value is defined as the percentage of concave downward cells within a constant radius (Iwahashi & Pike, 2007). Here, a 10 cell radius was used.
Terrain Ruggedness Index (TRI)	A quantitative measure of surface heterogeneity and can be explained as the sum change in elevation between a central pixel and its neighborhood (Riley et al, 1999). Here, a 10 cell radius was used.

### 3.2 Optical Data Acquisition & Post Processing

165 High-resolution optical data (20.2 Megapixels) was acquired by the DeepSurveyCamera system on board AUV Abyss  
(Kwasnitschka et al., 2016). During image acquisition the altitude above ground was 5 to 11 m, resulting in an overlap  
between the images of ca. 60% in each direction. In total, 11,276 photos acquired in block G77 (Greinert, 2017) and  
analysed with the automated image analysis algorithm CoMoNoD (Schoening et al., 2017a, 2017b and 2017c). For each  
170 image this algorithm delineates each individual Mn-nodule and provides quantitative information on each nodule (size in  
cm<sup>2</sup>, alignment of main axis, geographical coordinate of the nodule). This information is further aggregated per image to  
provide the average number of Mn-nodules per square meter (Mn-nodules/m<sup>2</sup>), the nodule coverage of the seafloor in  
percent and the nodule size distribution in cm<sup>2</sup> size quantiles. The algorithm has successfully been applied for quantitative  
assessment and predictive modelling of Mn-nodules (Peukert et al., 2018a, Alevizos et al., 2018). Nevertheless, the derived  
175 number of Mn-nodules/m<sup>2</sup> is subject to uncertainties due to the limitations of the CoMoNoD algorithm and the non-constant  
altitude of the AUV, especially in areas with slopes. The CoMoNoD algorithm cannot detect sediment-covered Mn-nodules  
due to the low or non-existent contrast. It may count two or more adjacent small Mn-nodules as one big nodule or  
misinterpret benthic fauna or rock fragments with similar visual features as Mn-nodules. The CoMoNoD algorithm fits an  
ellipsoid around each detected Mn-nodule, which limits the first two disadvantages as it splits huge Mn-nodules and  
accounts for potentially buried parts (see discussions in Schoening et al., 2017a). In general, the first two disadvantages lead  
180 to underestimations while the third one results in an overestimation of the number of Mn-nodules per m<sup>2</sup>. These limitations  
are common and the need for corrections between optical and box-corer data has been acknowledged (Sharma and Kodagali,  
1993; Sharma et al., 2010 and 2013; Tsune and Okazaki, 2014; Kuhn and Rathke, 2017). Recent studies show that the  
difference between image estimates and the abundance in box corer data (due to sediment covered Mn-nodules) can be two  
to four times higher (Kuhn and Rathke, 2017). In this study, none of the box-corers was obtained exactly at a location for  
185 which optical data exists, thus no direct comparison and verification exist. Taking box corer samples for verification requires  
Ultra Short Baseline (USBL) navigation and imaging of the seafloor prior to the physical sampling. The effects of the non-  
constant flying altitude on the detection of Mn-nodules per m<sup>2</sup> are explained in detail below. For each photo location, the  
depth and the bathymetric derivative values were extracted from the **hydroacoustic** data. As no absolute geo-referencing  
could be performed for the AUV-based photo surveys, drifting sensor data will have an effect on the alignment between  
190 bathymetric and photo information, which was considered, while interpreting the results.

### 3.3 Data Exploration and Spatial Analysis

The data exploration, spatial plotting and analysis was performed with ArcMap™ 10.1, PAST v3.19 (Hammer et al., 2001),  
and R (R, 2008). All data were projected as UTM Zone 10N coordinate system (to enable spatial analysis). The existence of  
spatial autocorrelation in the distribution of Mn-nodules/m<sup>2</sup> was examined by the Global Moran's Index (GMI) and Anselin  
195 Local Moran's Index (LMI). Both, GMI (Moran, 1948 and 1950) and LMI (Anselin, 1995) are well-established for  
examining the overall (global) and local spatial autocorrelation, respectively (e.g. Goodchild, 1986; Fu et al., 2014). GMI  
attains values between -1 and 1 with high positive values indicating strong spatial autocorrelation. High positive LMI index

values indicate a local cluster. This cluster could be a group of observations with high-high (H-H) or low-low (L-L) values regarding the examined variable. A high negative index value implies local outliers, like high-low (H-L) or low-high (L-H) clusters, in which an observation has a higher or lower value in comparison to its adjacent observations. Both Moran's Index analyses were performed in ArcMap™ 10.1 (for parameter settings see Appendix A). One decimal was retained in the presentation of the results from statistical analysis and RF modelling.

### 3.4 Box corer Data

A total of five box-corers (0.5 m x 0.5 m surface area) were obtained close to the study area (coordinates not given due to confidentiality). However, one is located within Block G77 (Figure 3a); this is the result of independent sampling schemes and purposes during the cruise. Nevertheless, all box core samples (maximum distance <1.5 km), were analyzed and used for further analyses. In each box-corer, the number, size, and weight of nodules were measured and the abundance (kg/m<sup>2</sup>) was estimated (mean value: 26.5 kg/m<sup>2</sup>). The total number of Mn-nodules within each box corer was compared with the number of Mn-nodules on the surface resulting in an average ratio of 1.32 (Table 2). This means that ≈ 25% of the nodules are not seen on the surface but are completely buried within the sediment (down to a depth of about 15 cm).

**Table 2.** The number of Mn-nodules on the sediment surface, the total number of Mn-nodules per box core, the ratio of those two values, and the distance of the box corer deployments from the study area in block G77.

box corer station	total number of Mn-nodules	number of Mn-nodules at the surface	ratio	abundance (kg/m <sup>2</sup> )	distance from G77 area (km)
BC20	40	27	1.5	-	0
BC21	67	58	1.1	27.1	1.4
BC22	29	21	1.4	27.1	0.6
BC23	32	20	1.6	25.2	0.1
BC24	17	16	1.0	-	1
<b>Average</b>	<b>37</b>	<b>28</b>	<b>1.32</b>	<b>26.5</b>	<b>0.6</b>

### 3.5 RF Predictive modelling

The RF modelling was performed with the Marine Geospatial Ecology Tools (MGET) toolbox in ArcMap™ 10.1. MGET (Roberts et al., 2010) uses the *randomForests* R package for classification and regression (Liaw and Wiener, 2002). Our target variable (number of Mn-nodules/m<sup>2</sup>) is continuous, so regression was applied. We followed the three main steps to establish a good model by selecting predictor variables, calibration/training of the model and finally validating the model results.

Selection of Predictor Variables: The depth (D) and its derivatives (Table 1) were used as predictor variables. Although RFs can handle a high number of predictor variables with similar information, the exclusion of highly correlated variables can improve the RF performance and decrease computation time (Che Hasan, 2014; Li et al., 2016). Thus, the correlation between derivatives was investigated using the Spearman's rank correlation coefficient. None of the variable pairs was highly perfectly correlated ( $\rho \geq 95$ ) and consequently, all of them were used for RF modelling (Appendix A).

Calibration of the model: During the calibration process, the RF parameters were adjusted as follows. The number of predictor variables to be randomly selected at each node (*mtry*), the minimum size of the terminal nodes (*nodesize*) and the number of trees to grow (*ntree*) were set to the default values, in order to investigate the optimum training size. For regression RF the default *mtry* value is 1/3 of the number of predictor variables (rounded down), *nodesize* is 5 and *ntree* is 500 (Liaw and Wiener, 2002). RF has demonstrated to be robust regarding these parameters and the default values have given trustworthy results (e.g. Liaw and Wiener, 2002; Diaz-Uriarte and de Andres, 2006; Cutler et al., 2007, Okun and Priisalu, 2007; Li et al., 2016 & 2017). With regards to the subsampling method (*replace*), the subsampling without replacement was selected. Although the initial implementations of the RF algorithm use subsampling with replacement (Breiman, 2001a), later studies showed that this process might cause biased selection of predictor variables that vary in their scale and/or in their number of categories, resulting in a biased variable importance measurement (Strobl et al., 2007, 2009; Mitchell, 2011). Based on recent findings, the raw variable importance was preferred (*unscaled*) as the final parameter (Diaz-Uriarte and de Andres, 2006; Strobl et al., 2008a, 2008b, 2009). Using these settings, the influence of the training sample size was examined (10 to 90% of the total sample in steps of 10%) and compared based on the Mean of Squared Residuals (MSR) using the respective equation provided in the *randomForests* R package (Liaw and Wiener, 2002). The different training groups need to be considered as representative of the total sample, in order to capture the heterogeneity of the Mn-nodules' spatial distribution. The spatially random selection of subsamples by MGET ensured similar statistical characteristics in each group (Appendix A). For each case of different training sample size, the model was run ten times and the results are presented as the average value of these ten runs (Appendix B). Since the optimal training sample size was defined, the influence of the number of growing trees (*ntree*) and the influence of the number of predictor variables to be randomly selected at each node (*mtry*) was examined. Only for the already defined optimum training size ten different *ntree* values (100 to 1000 in steps of 100) and seven different *mtry* values (1 to 7 in steps of 1) were tested and compared based on the MSR values. In each case of different *ntree* and *mtry* parameter, the model was run ten times and the results are presented as the average value of these ten runs (Appendix B).

Selection and external validation of the optimal model: Based on the above-mentioned results and considering the sampling and computational cost, the optimal model was selected, run for 30 iterations and applied to the entire study area. Its predicted values were validated with the observed values from the remaining dataset that was not used. Several validation measures were used including the Mean Absolute Error (MAE), the Mean Squared Error (MSE) and the Root Mean Squared Error (RMSE). The combined use of MAE and RMSE is a well-established procedure as the MAE can evaluate better the overall performance of a model (all individual differences have equal weight), while the RMSE gives disproportionate weight to large errors showing an increased sensitivity to the presence

of outliers. Due to this characteristic RMSE is suitable for outlier detection analysis but should not be used solely as an index for the model performance (Willmott & Matsuura, 2005). Both, MEA and RMSE are measured in the same unit as the data. In addition, the  $R^2$ , Pearson ( $r$ ) and Spearman's rank correlation coefficients were used to identify the correlation between predicted and initial values. Finally, the descriptive statistics of predicted and initial values were compared and a residual analysis was performed.

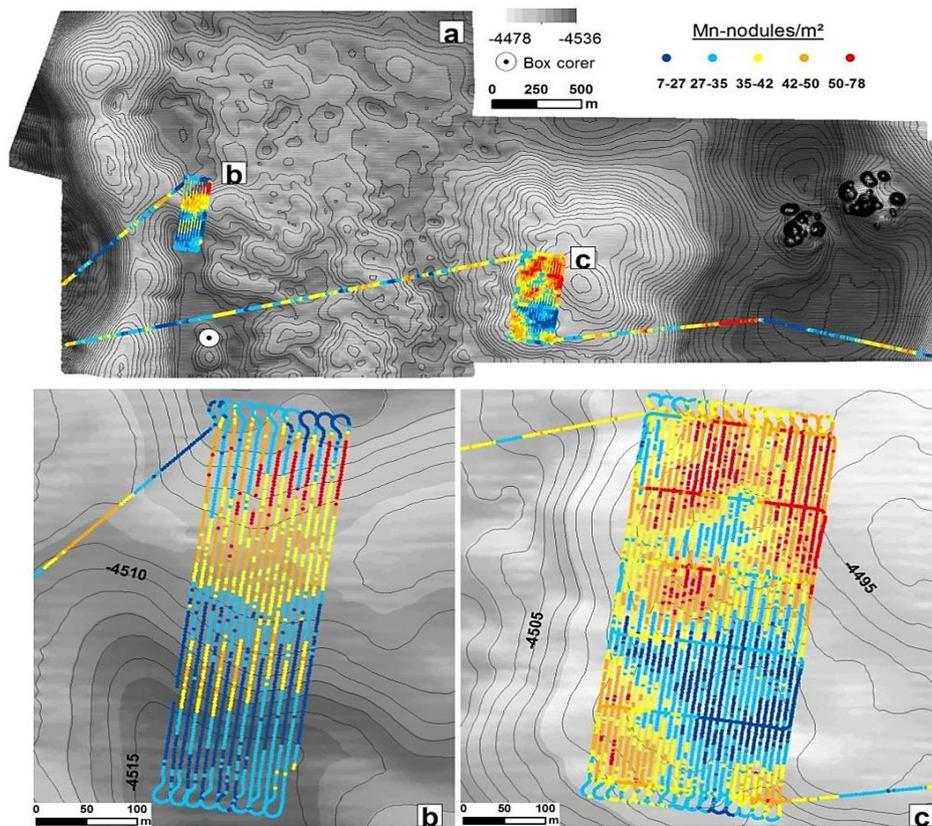
### 3.6 Resource Assessment

As the optimal RF model was applied to the entire Block G77, an estimate of the abundance ( $\text{kg/m}^2$ ) was computed, based on the analogy between the corresponding abundance measured from the average number of Mn-nodules in the box corer data and the number of Mn-nodules/ $\text{m}^2$  in each cell of the final result of the RF model. Considering that the collector can recover buried Mn-nodules from a maximum depth of 10-15 cm (Sharma, 1993 and 2010), the ratio of 1.32 was applied to account for Mn-nodules not detected in the images, and areas with a slope of  $>3^\circ$  were excluded, assuming that a potential mining vehicle is limited to less steep slopes (UNOET, 1987).

## 4. Results

### 4.1 Data Exploration

The analysis of AUV photos with the CoMoNoD algorithm (Schoening et al., 2017a) revealed a rather heterogeneous pattern of Mn-nodules/ $\text{m}^2$  in the study area, showing adjacent areas with high and low Mn-nodules number (Figure 3a). The number of Mn-nodules/ $\text{m}^2$  changes within less than 100m in the overall study area and in the two main sub-areas b and c (Figures 3a-c). This heterogeneity causes the large range of Mn nodules/ $\text{m}^2$  (Figure 3a). In half of the photos (48%), the number of Mn-nodules/ $\text{m}^2$  varies from 30 – 43 with the mean value being 36.6 Mn-nodules/ $\text{m}^2$ . The very small alternation change of 5% trimmed mean value indicates the absence of extreme outliers, which is confirmed by box-plot analysis (Appendix B). Further analysis of their descriptive and distribution characteristics was performed in order to assess the presence of normality in the data, resulting that the number of Mn-nodules/ $\text{m}^2$  is approximately normal distributed. Although the presence of normality in data is not a prerequisite assumption in order to perform the RF (Breiman, 2001a); as it is with geostatistical interpolation techniques like kriging (e.g. Kuhn et al., 2016), this examination can give us a better understanding of the Mn-nodules' distribution inside the study area, and it is an important step in order to examine potential extreme observations which may be derived from wrong measurements and could artificially change the training range during RF predictive modelling. Moreover, absence of linear correlation was observed between Mn-nodules/ $\text{m}^2$  and the produced bathymetric derivatives, indicating the complexity of the phenomenon (Appendix B).



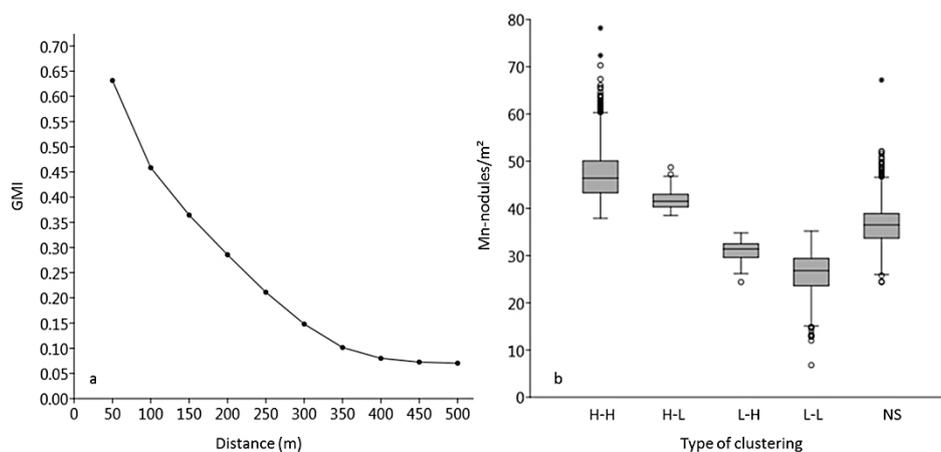
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**Figure 3.** a) The spatial distribution of Mn-nodules/m<sup>2</sup> inside block G77 and the box corer position. b) The spatial distribution of Mn-nodules/m<sup>2</sup> inside the sub-area b. c) The spatial distribution of Mn-nodules/m<sup>2</sup> inside the sub-area c.

#### 4.2 Spatial Analyses

Spatial analyses revealed the presence of a spatial autocorrelation in the distribution of Mn-nodules/m<sup>2</sup>. The GMI, with  
 290  $I=0.6989$ ,  $p<0.01$  and  $Z\text{-score}>2.58$  indicates a positive spatial autocorrelation. According to the incremental analysis, the  
 index takes its highest value in the first 50 m with a gradual decrease, approaching 0 values **after a distance of 400 m** (Figure  
 5a). Similarly, the results from the LMI show that the main size of the spatial clusters does not exceed 400m in either  
 direction (Figure 6a). The main types of these clusters are H-H and L-L groups (Table 4 & Figure 6a). A distinct  
 ‘buffer/transitional zone’ with Mn-nodules was found between these two clusters, which does not show a significant  
 295 autocorrelation (Figure 6b & 6c). Approximately one-third of the data does not have a significant clustering (NS). In the sub-  
 area c, in the outer parts of these zones without significant spatial clustering, the few local H-L and L-H groups are located.

Both H-L and L-H (from the entire study area) only account for 2.1% of the data (Table 4). The comparison of the number of Mn-nodules/m<sup>2</sup> between the groups shows a clear discrimination between H-H and L-L clusters (Figure 5b). The H-H clusters are in areas with 37.9-78.2 Mn-nodules/m<sup>2</sup> whilst the L-L clusters are in areas with 6.8-35.2 Mn-nodules/m<sup>2</sup>.

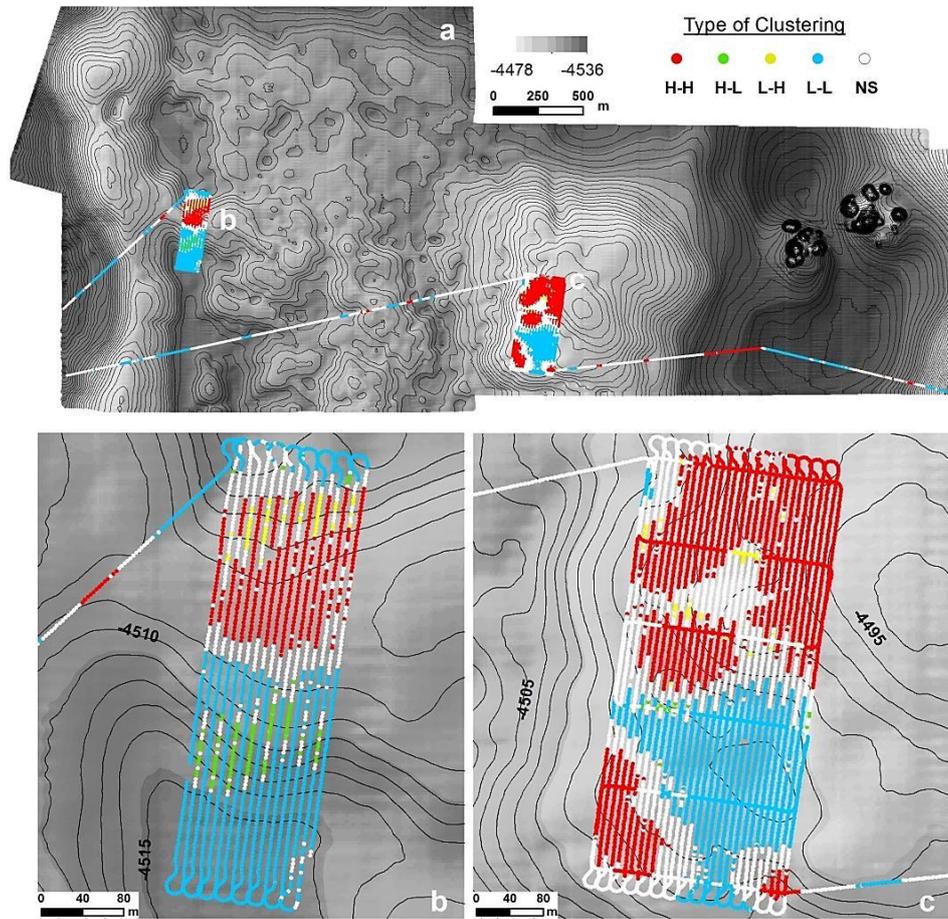


300

**Figure 5.** a) The GMI decrement due to increasing distance, after the first 50m. b) The range of Mn-nodules/m<sup>2</sup> in each clustered group.

**Table 4.** Number and % percentage of samples in each type of spatial clustering.

Cluster Type	H-H	H-L	L-H	L-L	NS
Counts (n)	3472	121	113	3523	4047
Counts (%)	30.8	1.1	1.0	31.2	35.9



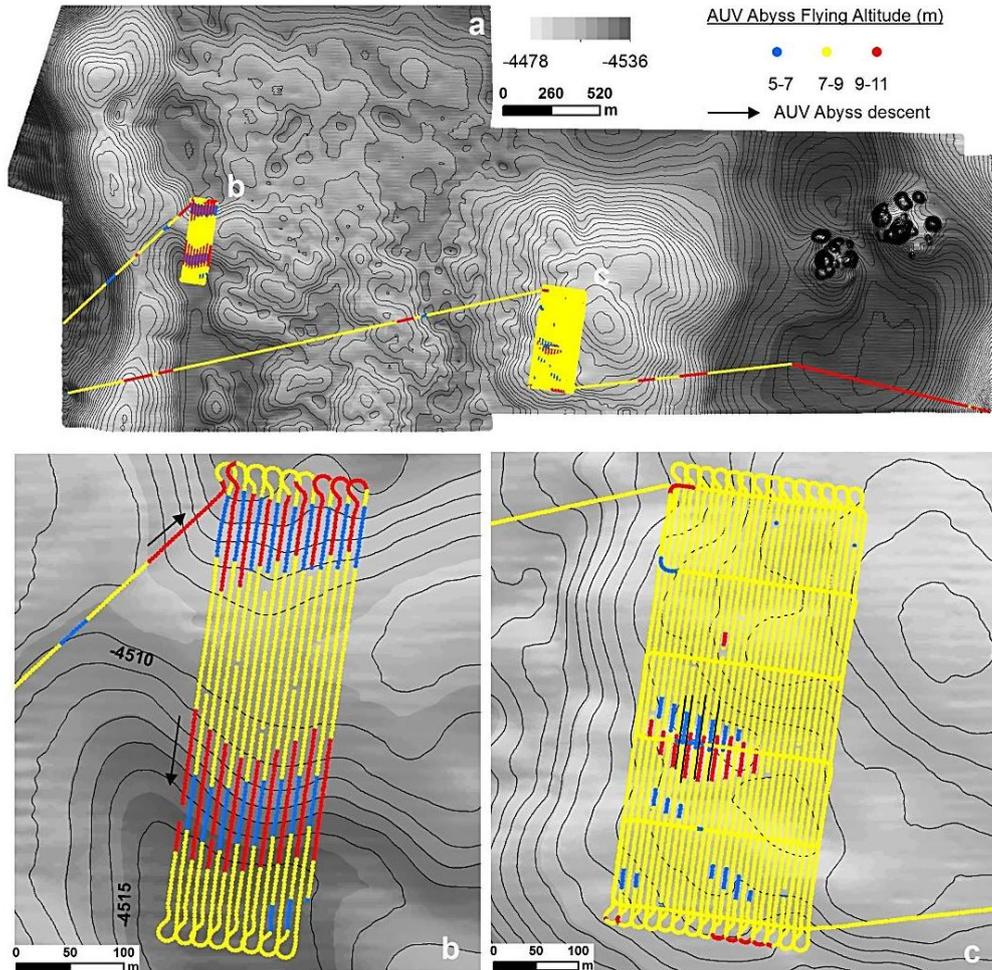
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**Figure 6.** a) The spatial distribution of the significant cluster types inside the block G77. b) The spatial clusters inside the sub-area b. c) The spatial clusters inside the sub-area c

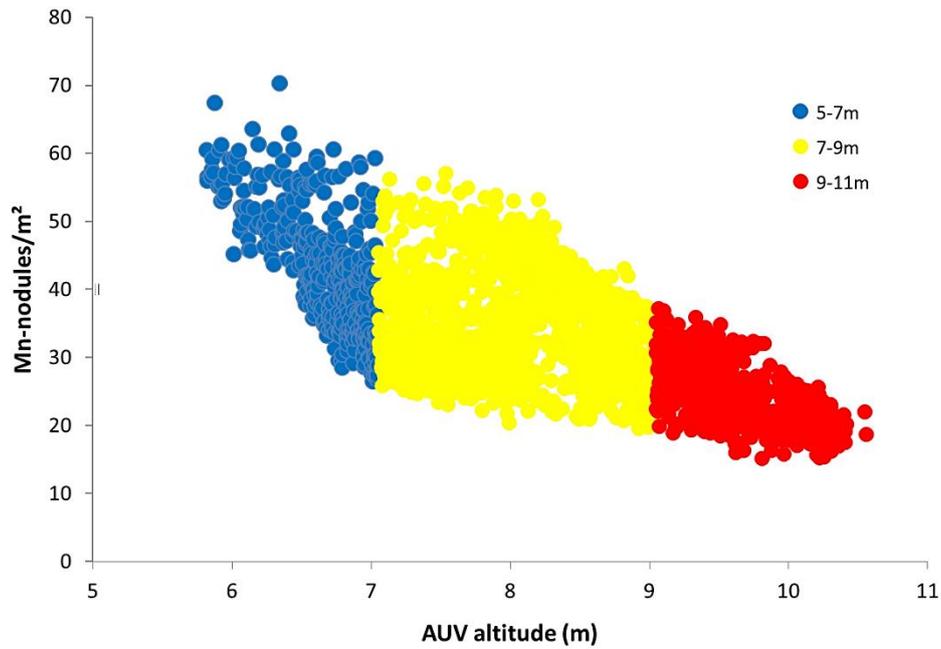
The application of the LMI reveals a bias that exists in the data due to the sampling procedure, especially in the sub-area b (Figure 6b). Here, the presence of the slope around  $2.8^\circ$  forced the AUV to vary its altitude between the ascending and descending phase (Figure 7b). This variation seems to affect the image quality resulting in counting fewer nodules for higher altitudes of the AUV (Figure 8 & 9). This is also confirmed by the distribution map of the Mn-nodules/m<sup>2</sup> (Figure 3b). It is important to emphasize that this difference clearly shows up in the LMI results (Figure 6b) and not in the distribution map (Figure 3b); here the arbitrary choice of color scale can hide this bias during plotting. The comparison of the detected Mn-nodules/m<sup>2</sup> in these adjacent lines, inside the small sub-area b, gives a ratio  $\approx 1.4$  between photos that have been acquired in 7-9 m altitude and those in 9-11 m altitude. The ratio is higher ( $\approx 1.8$ ) between photos from 5-7 m and 9-11 m altitude. In contrast, the ratio between photos from 5-7 m altitude and those in 7-9 m altitude is  $\approx 1.25$  indicating that the problem mainly exists in upper and lower flying altitudes. Despite their different ratio, none of these groups contain extreme high or low

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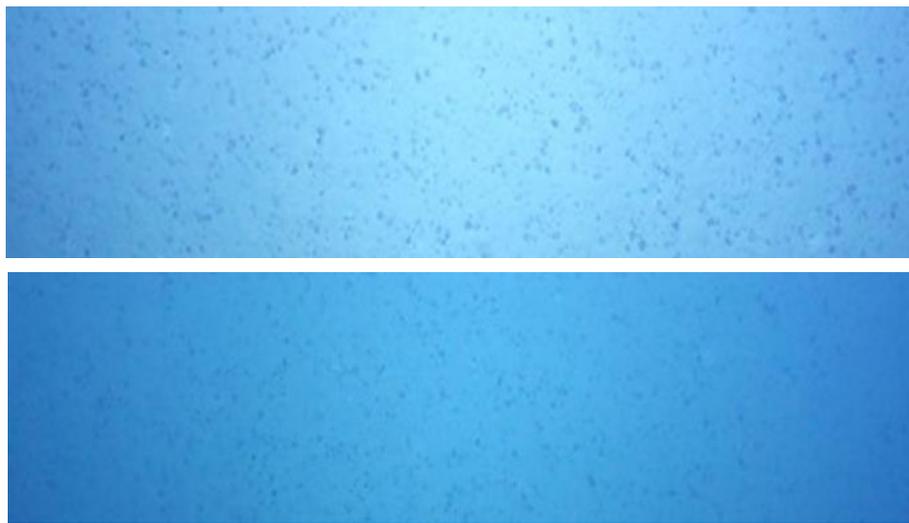
320 values of Mn-nodules/m<sup>2</sup>. Moreover, in several parts of the block, the photos from higher altitude are the only source of information without the ability for further comparison and consequently, they cannot be excluded from the modelling procedure.



325 **Figure 7.** a) The altitude of AUV Abyss inside block G77. b) The altitude inside the small sub-area b, where the presence of the slope forces the AUV to modify its altitude, flying closer to the seafloor in the ascending phase (blue lines) and farther from the seafloor in the descending phase (red lines). c) In the big sub-area c, the AUV flying altitude is mainly constant between 7-9 m for the entire part.

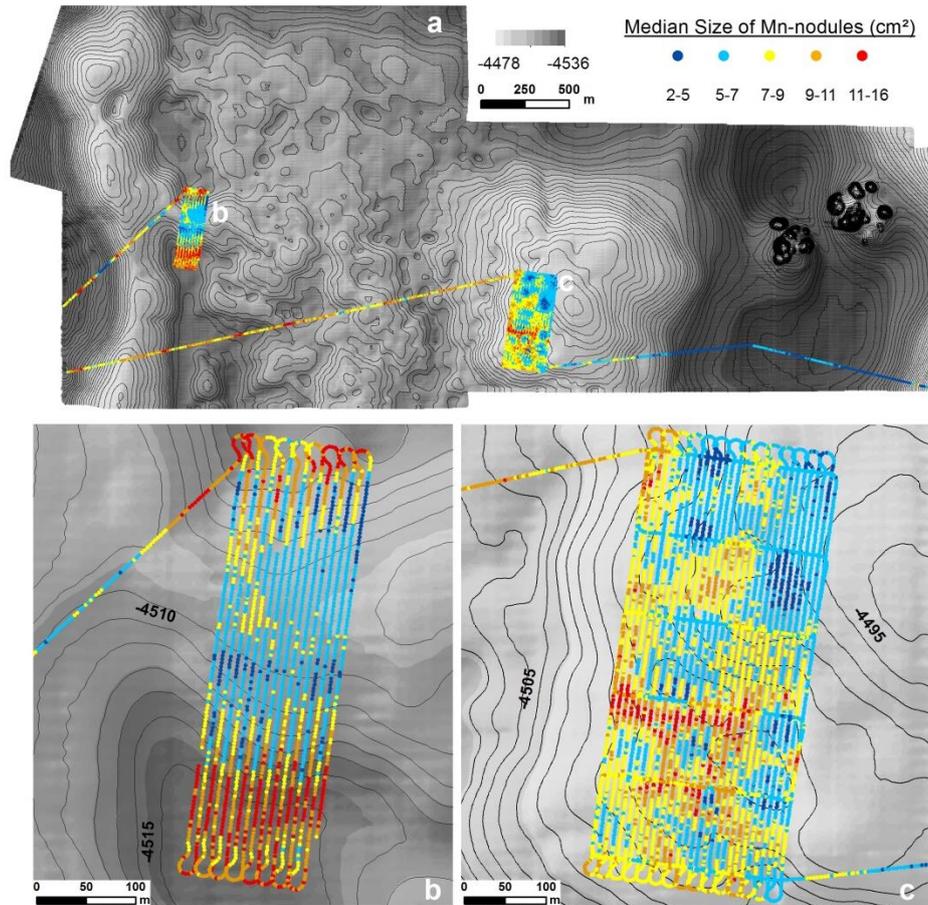


**Figure 8.** Scatterplot of the AUV altitude (m) and the estimated number of Mn-nodules/m<sup>2</sup> inside sub-area b. The colours correspond to the colour scale in figure 7.

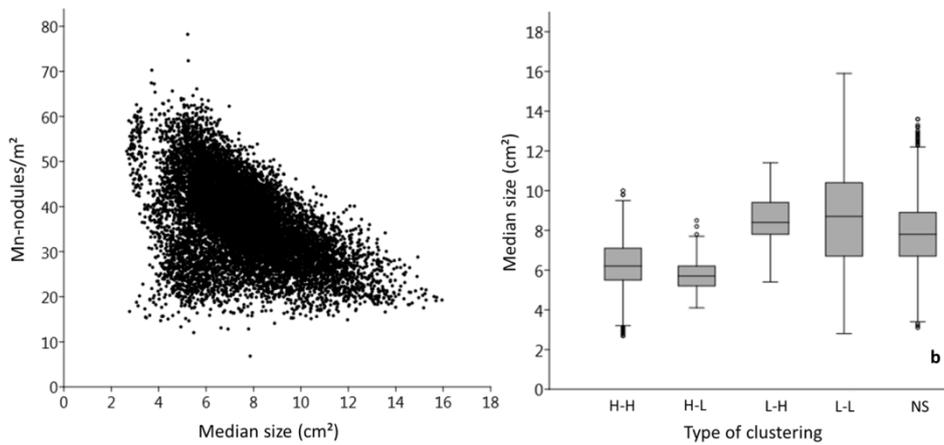


**Figure 9.** Adjacent AUV photos from consecutive dive tracks that have been obtained inside sub-area b, from: a) lower (5-7 m) and b) higher (9-11 m) altitude. Notice the decrement in the image brightness. (The area of the photos represent the central part of the photo, ca. 1/4 of the original photo size).

335 Spatial distribution of median size: Plotting of the median size in  $\text{cm}^2$  (Figure 10) showed that the number of Mn-nodules/ $\text{m}^2$   
is anti-correlated to the median Mn-nodule size. The Spearman's rank correlation coefficient and  $R^2$  between these two  
variables are -0.50 and 0.25 respectively, supporting this observation (Figure 11a); other studies found similar results  
(Okazaki and Tsune, 2013; Kuhn and Rathke, 2017; Peukert et al., 2018a). The box plot analysis of the median size values  
340 values (2.8 to 15.9  $\text{cm}^2$ ), the H-H group does not contain values above 10  $\text{cm}^2$  (2.7-10  $\text{cm}^2$ ). This means in consequence that  
in areas with significant clustering of higher numbers of Mn-nodules/ $\text{m}^2$  the size of Mn-nodules tends to be smaller (Figure  
11b).



**Figure 10.** a) The spatial distribution of median Mn-nodule size (in  $\text{cm}^2$ ). b) The estimation of median Mn-nodule size in  
345 sub-area b and mainly in its southern part has been probably affected by the non-constant altitude of the AUV. c) The  
distribution of the median size inside sub-area c shows **also** a clumped pattern, **too**.



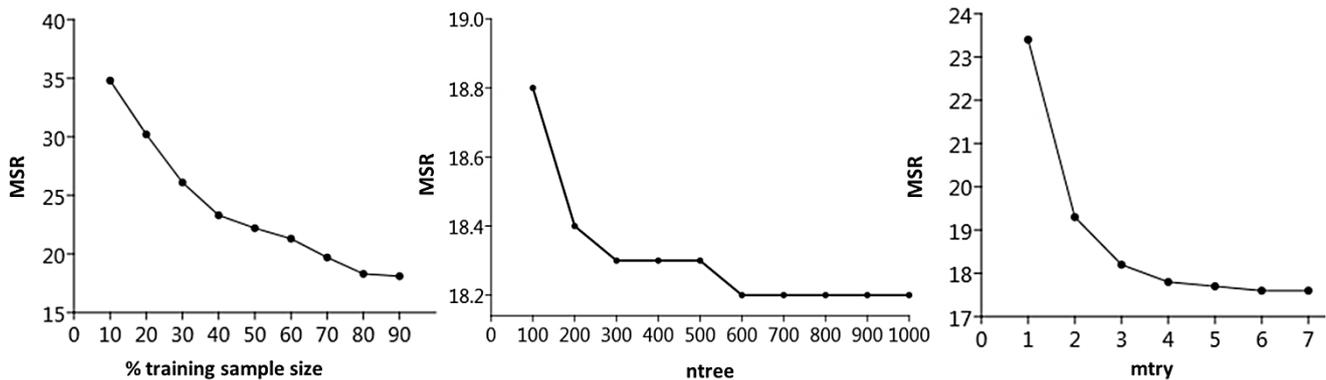
**Figure 11.** a) The plot of median size (cm<sup>2</sup>) and number of Mn-nodules/m<sup>2</sup>. e) The range of median size (cm<sup>2</sup>) in type of cluster. Notice the distinct difference in the range between the H-H and L-L cluster type.

### 4.3 RF Predictive modelling

#### 4.3.1 Effect of training sample size, *n*tree and *m*try parameter

The results of the modelling procedure demonstrate that the RF algorithm is influenced by the size of the training sample (Figure 12a). This finding is in accordance with other studies, in which larger training samples tended to increase the performance of RF (Li et al., 2010 and 2011b; Millard and Richardson, 2015). The inclusion of a more representative range of the observed values and consequently larger spectrum of the causal underlying relationships, assist the RF to build a better model for the prediction of the value distribution inside the study area. **For our data,** the decrement becomes smaller when the size of the training sample increases further; it reaches a minimum value of 0.2 between 80% and 90%, showing that these additional 10% do not notably benefit the RF model. However, the absence of stabilization of the error to a minimum value indicates that more optical data are needed from this block. The small decrement in error between 80% and 90% was the decisive factor to select 80% of the data as training samples (also considering the larger number of remaining validation data and the reduced computational effort). Based on this dataset, the examination of different numbers of trees showed that the RF error remains constant after 600 trees (Figure 12b). Less trees result in a larger error; this particularly becomes evident with less than 300 trees. With more than 300 trees the range of the error is reduced (Appendix B). A higher number of trees enables higher *m*try values as there are more opportunities for each variable to occur in several trees (Strobl et al., 2009). Similarly to the *n*tree parameter, a larger number of *m*try values results in a reduced error (Figure 12c). The error reaches a minimum and cannot be reduced further for *m*try = 6; with values below 3 the error increases significantly. The different numbers of *n*tree reduced the error by only 0.6 in the MSR (from 18.8 to 18.2), in contrast different *m*try values reduced the error by 5.8 in the MSR (23.4 to 17.6), highlighting its importance for the prediction accuracy. In general a

370 higher number of *mtry* values is suggested for RF studies with correlated variables to result in a less biased result regarding the importance of each variable; this is because the higher number increases the competition between highly correlated variables, giving more chances for different selections (Strobl et al., 2008a). The finally selected *mtry* value of 6 coincides with the recommended approach for *mtry* (default, half of the default, and twice the default) suggested by Breiman (2001a). Albeit the importance of this analysis, within the model with 80% of the data as training sample, the decrease in error by the use of RF tuned values instead of RF default values was only 0.7 in the MSR values, whilst the greatest reduction in error (16.5 in the MSR values) came from the increase in training data set size. This highlights the increased sensitivity of the method with respect to training data and that the recommended settings in the R *randomforest* package (Lia and Wiener, 2002) give trustworthy results, increasing its simplicity and operational character.



380 **Figure 12.** a) The effect of training sample size in RF error (in MSR). b) The effect of *ntree* parameter in RF error (in MSR) for the 80% training size. c) The effect of *mtry* parameter in RF error (in MSR) for the 80% training size.

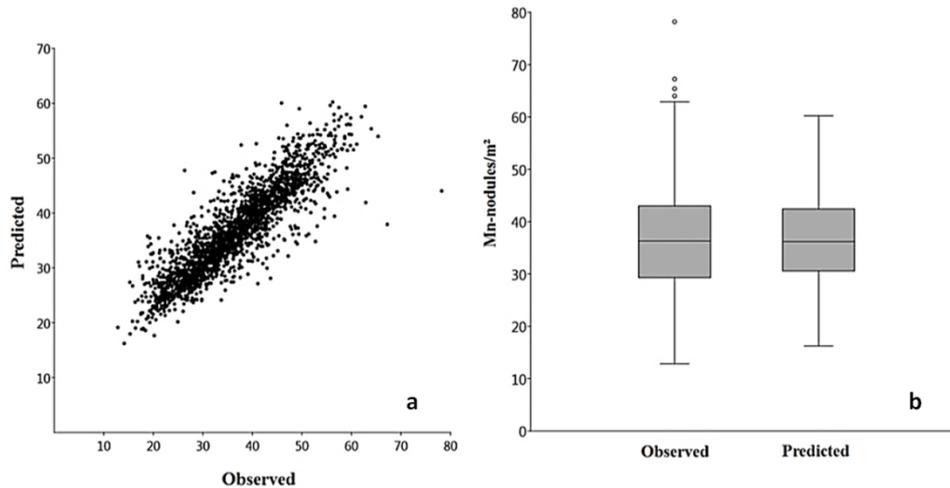
#### 4.3.2 Selection, application and external validation of the optimal model

Based on the above-mentioned findings, the optimal RF regression model which uses 80% of training data, 600 trees and 6 predictor variables to be randomly selected at each node, was selected and applied to the entire block G77. The comparison of the predicted values with the observed values from the remaining 20% (2,255 observations) of validation data showed a good predictive performance (Table 5). Analytically, MAE and RMSE have very low values,  $R^2$  has a high value and both Pearson's and Spearman's correlation coefficients show a strong positive correlation between the predicted and observed values. The small deviation between MAE and RMSE and the same good correlation of the Pearson and Spearman factor point towards the absence of extremely high or low predicted values (outliers). Moreover, the performance is rather stable among all the iterations (Appendix B).

**Table 5:** The values of validation measures between predicted and observed data.

MAE	MSE	RMSE	R <sup>2</sup>	Pearson	Spearman
3.1	19.0	4.4	0.8	0.9	0.9

The scatterplot and box plot (Figure 13a and 13b) illustrate this good match between predicted and observed values, as confirmed also by the descriptive statistics, which have almost equal mean, median, skewness and kurtosis values (Table 6).  
 395 The residual analysis confirmed further the robustness of the model (Appendix B).



**Figure 13.** Comparison between observed and predicted values: scatterplot (left) and box-plots (right)

**Table 6.** Descriptive statistics of observed and predicted values

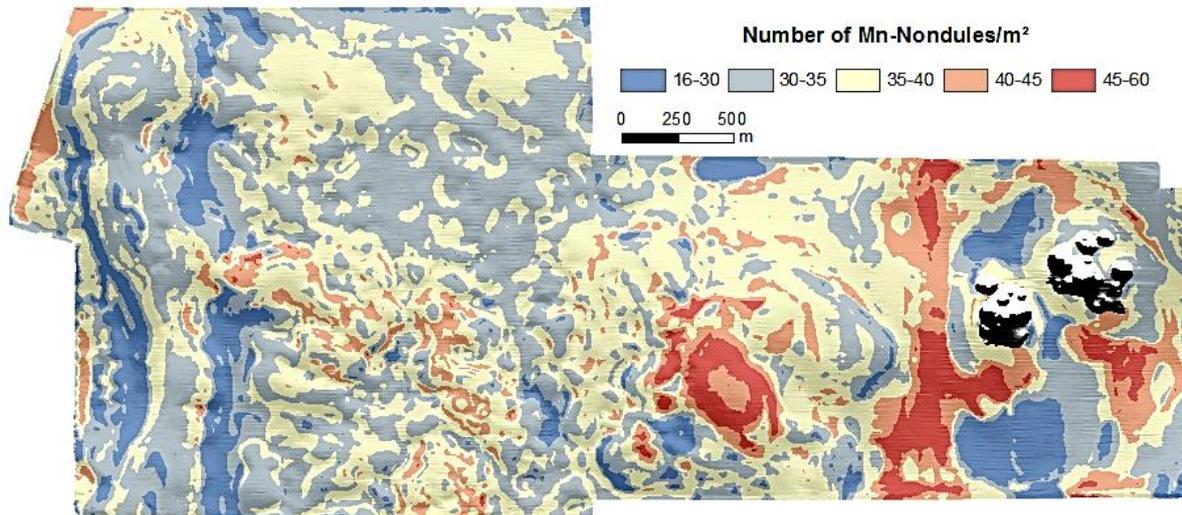
	Mean	Std. Error	5% Trim. Mean	Median	Mode	SD	Min.	Max.	C.L (95%)
Observed	36.5	0.2	36.3	36.3	40.8	9.4	12.8	78.2	0.4
Predicted	36.7	0.2	36.5	36.2	33.9	7.8	16.2	60.2	0.3

The statistical analysis also reveals the limitations of the RF model which cannot predict beyond the range of training values.  
 400 It underestimates the maximum predicted values and overestimates the minimum values (Figure 13b & Table 6), a limitation also mentioned by other authors (e.g. Horning, 2010). This happens, because in regression RF the result is the average value of all the predictions (Breiman, 2001a).

#### 4.3.3 RF predicted distribution of Mn-nodules/m<sup>2</sup>

The final application of the RF model for the entire block G77 predicts that the majority of the area is covered by 30-45 Mn-nodules/m<sup>2</sup> (Figure 14). In the central-western part the distribution is quite uniform (at this scale) with few small areas of  
 405

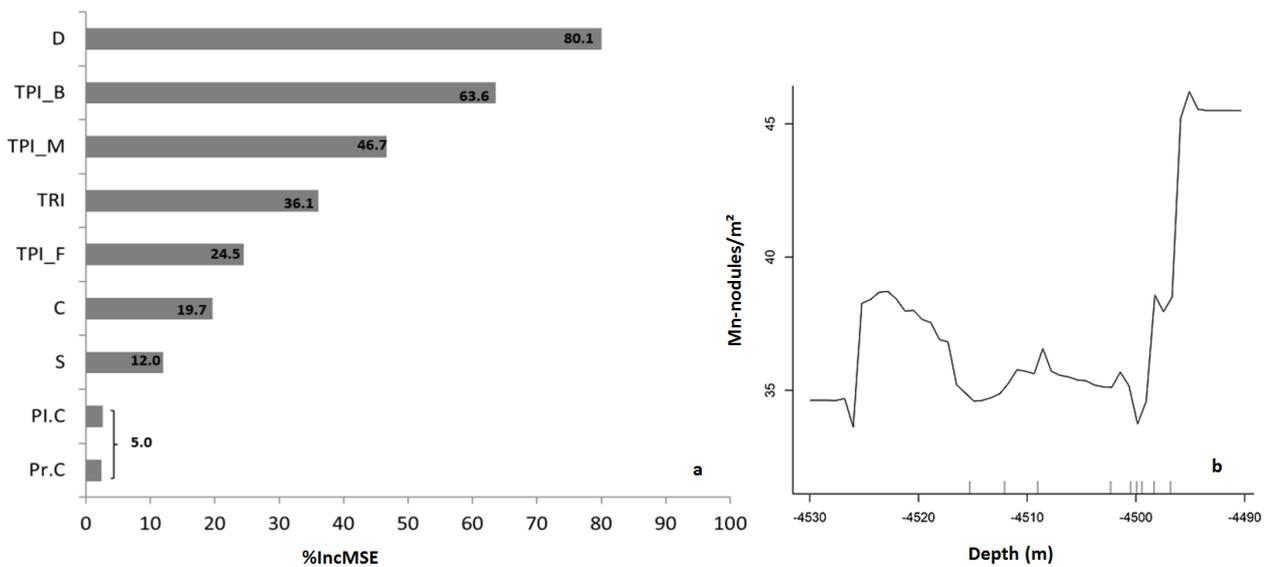
lower numbers. In the western part, there are two extended areas along the base of the hill with the lowest number of Mn-nodules/m<sup>2</sup>. Both of these areas have a linear shape in N-S direction and follow the seafloor topography with increased slope (>3°). The third main patch with minimum Mn-nodules/m<sup>2</sup> occurs in the eastern depression part. In contrast, areas of higher number of Mn-nodules/m<sup>2</sup> are located mainly in the central upper part of the hill and eastward facing slope of eastern depression and south of the sub-recent hydrothermally active area.



**Figure 14.** The RF predicted distribution of Mn-nodules/m<sup>2</sup> inside block G77.

#### 4.3.4 RF importance

The analysis of the RF variable importance showed that the best explanatory variable for the distribution of Mn-nodules/m<sup>2</sup> is depth (Figure 15a). The partial dependence plot of depth shows that there are specific ranges of the depth ranges, which promote higher numbers of Mn-nodules/m<sup>2</sup> aggregated in a nonlinear way (Figure 15b). Such nonlinear relationships between predictor and response variables have already been described in the past, both in marine (e.g. Zhi et al., 2014; Li et al., 2017) and terrestrial environments (e.g. Cutler et al., 2007). The following two most important variables are the TPI\_B and TPI\_M. TRI, TPI\_F, C, and S follow in importance (Figures 15a). All of them also contribute in a nonlinear way. (Appendix B). Pl.C and Pr.C do not contribute significantly as explanatory variables in the performance of the RF model (Figure 15a and Appendix B). Although the RF demonstrates good overall performance, the small study area and the arbitrary choice of the spatial scales for the TPI and other derivatives, limit the potential of these variables as indicative explanatory variables on a broader scale. It is well established that surface derivatives are scaled-dependent with different analysis scales to create alterations in results. Thus the combined use of different scales (here TPI) in the analysis and modelling procedure can produce models that do capture the natural variability and scale dependence (Wilson et al., 2007; Miller et al., 2014; Ismail et al., 2015; Leempoe et al., 2015).

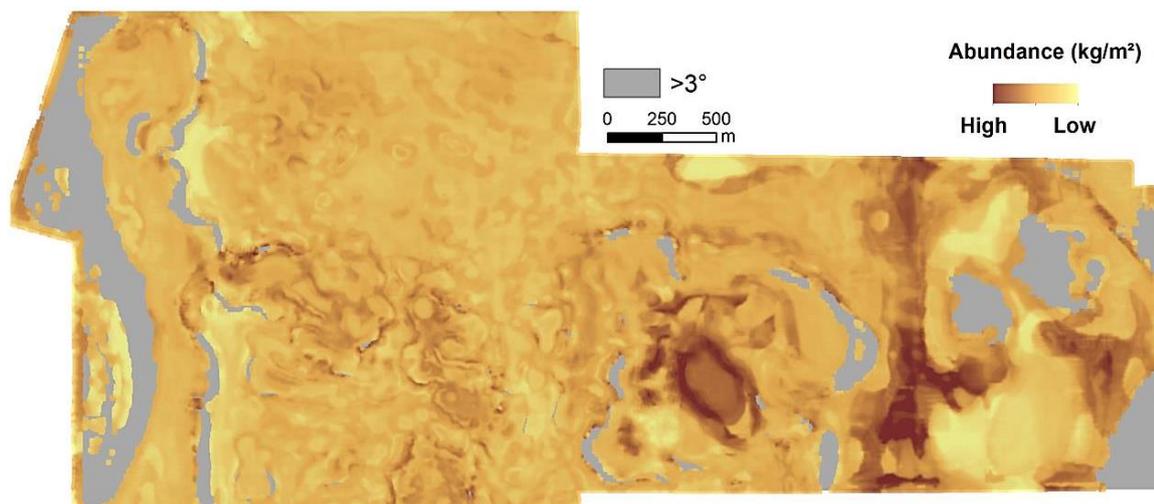


**Figure 15:** a) The variable importance of each predictor in the RF model. b) The partial dependence plot of the Depth (right). The ticks inside the graphs indicate the deciles of the data.

#### 430 4.3.5 Estimation of abundance (kg/m<sup>2</sup>) of Mn-nodules

The predicted Mn-nodule distribution was combined with the abundance from box corer data (and corrected with the ratio between buried/unburied Mn-nodules, in order to include the top ~15 cm of the sediment), resulting in the Mn-nodules' abundance map shown in Figure 16. According to this map, block G77 is a promising area for mining operations. The entire block is above the cut-off abundance of 5 kg/m<sup>2</sup> (UNOET, 1987), with a mean value of 33.8 kg/m<sup>2</sup>. We calculated that 84% of block G77 has slopes below 3°, steeper slopes are located mainly at the outer parts of the block, a fact that would ease establishing an ideal mining path. In this respect, the AUV-scale mapping provides vital information for a potential mining path by decreasing the possibility of machine failure due to poorly mapped steep slopes not detected e.g. by ship-based bathymetry (Peukert et al., 2018b). Mn-nodule distribution maps with this resolution increase the mining efficiency because local deposit variations can significantly affect the performance of the pick-up rate, which is likely determined by technical parameters of the mining vehicle as well as the size, burial depth and abundance of Mn-nodules in the seafloor (Chung, 1996). The exclusion of areas with slopes > 3° resulted in 8 km<sup>2</sup> mineable seafloor surface. Assuming a constant 80% collection efficiency (Volkman & Lehnen, 2018) and a 30% reduction of the Mn-nodule weight by removal of water (Das & Anand, 2017), the dry mass of Mn-nodules that can be extracted from the surface and the first 15 cm of the sediment column amounts to ca. 190,000 t. In a back-of-the-envelope calculation this quantity, assuming constant metal content inside the study area, equal to the average metal concentrations inside the CCZ (Table 7) (Volkman, 2015), and 90% metal recovery efficiency; could result in an estimated resource haul of 45,450 t Mn, 2,232 t Ni, 1891 t Cu, 374 t Co, and 102 t

Mo (Table 7).



**Figure 16:** The total abundance of Mn-nodules from the surface and embedded in the sediment (max. 15 cm), in areas with slope  $\leq 3^\circ$  inside block G77 (continuous values of abundance are not given due to confidentiality).

**Table 7.** The estimated amount of metal mass for 5 metals, based on the average values of metal content inside CCZ and a 5metal HCl-leach recovery method (Volkman, 2015).

Total Wet Mass (t):	270,400				
Total Dry Mass (t):	189,280				
Metal Content	Mn	Ni	Cu	Co	Mo
wt%:	26.68	1.31	1.11	0.22	0.06
Equal to (t):	50,500	2,480	2,101	416	113
90% metal recovery (t)	45,450	2,232	1,891	374	102

## 5. Discussion

We present a case study that highlights the applicability of the combination of AUV bathymetric and optical data for Mn-nodules resource modelling using RF machine learning. The use of AUVs for collecting hydroacoustic and optical data in areas of scientific and commercial interest can provide more precise bathymetric and Mn-nodules distribution maps. Regarding the bathymetric maps, the accurate and detailed reconstruction of the seafloor bathymetry in meter-scale resolution enables to use bathymetry and its derivatives as source data layers within a high-resolution RF model. **These data should have high quality characteristics, as the presence of acquisition artefacts may affect the robustness of the modelling**

460 procedure (Preston, 2009; Herkül et al., 2017). High-quality bathymetric data, as primary model explanatory variables, is a  
priori step, as the occurrence of acquisition artefacts may affect the robustness of the modelling procedure (Preston, 2009;  
Herkül et al., 2017). The combined use of cameras as the DeepSurveyCamera (Kwansnitschka et al., 2016) for acquiring  
high-resolution photographs, and an automated analysis with a state-of-the-art algorithm (Schoening et al., 2017a) provides  
essential quantitative information about the distribution of Mn-nodules. Image analysis results are more robust for constant  
465 AUV altitudes (7-9m) above flat areas ( $<3^\circ$ ), while the alternation of the flying altitude and camera orientation during the  
ascending & descending phases limit the quality of the obtained images and can affect the derived number of Mn-  
nodules/m<sup>2</sup>.

Inside block G77, the number of Mn-nodules/m<sup>2</sup> seems to follow a normal distribution without extreme outliers and without  
being linearly correlated with the used predictor variables. Spatially, a clumped autocorrelated pattern is demonstrated,  
470 mainly with clustered areas of H-H and L-L values. It is still unclear if this heterogeneity is caused by external processes  
(e.g. topographic characteristics, geochemical conditions, availability of nucleus material etc.) or it is resulted from the  
interaction of neighboring Mn-nodules. The areas with higher number of Mn-nodules could provide more fragments as  
potential nucleus material. However, the less available space in these areas may make more difficult the individual Mn-  
nodule growth, resulting in smaller median sizes. ~~Whether this heterogeneity is caused by external processes (e.g.~~  
475 ~~topographic characteristics, geochemical conditions, availability of nucleus material etc.) or reflects the interaction of~~  
~~neighboring Mn nodules is still unclear. The negative correlation between the number of Mn nodules/m<sup>2</sup> and the median~~  
~~Mn nodule size implies that may higher numbers of Mn nodules could provide more fragments as potential nucleus material~~  
~~at less available space and oxides for individual Mn nodule growth.~~ Conversely, a recent study from Kuhn and Rathke  
(2017) showed that the blanketing of the Mn-nodules by sediments is higher for larger Mn-nodules and, as a result, fewer  
480 large nodules will be counted; resulting in biased results in areas, where the Mn-nodules are bigger ~~regarding the areas with~~  
~~bigger size of Mn nodules.~~ Probably, all of these effects can happen at the same time (with different degrees of influence)  
promoting a given, scale-dependent spatial structure.

This study did not consider geochemical properties of the sediments as input data in the modelling process, which might give  
additional clues as to why Mn-nodules are distributed as they are. However, RF importance and partial dependence plots  
485 show that bathymetric and topographic factors tend to affect this distribution in a non-linear way and with the bulk of data  
plotting in specific ranges of the bathymetric derivatives. Such nonlinear relationships between predictor and response  
variables have already been described in the past, both in marine (e.g. Zhi et al., 2014; Li et al., 2017) and terrestrial  
environments (e.g. Cutler et al., 2007).

It should be acknowledged that the aim of any ML predictive model is to derive accurate predictions based on an existing  
490 (large) number of measurements, to capture a complex underlying relationship (e.g. non-linear and multi-variate) between  
different types of data, for which our theoretical knowledge or conceptual understanding is still under development  
(Schmueli, 2010; Lary et al 2016). Especially due to the constantly increasing size of scientific multivariate data in marine  
sciences, ML and RF are considered important analytic tools that can objectively reveal patterns of a (unknown)

phenomenon (Genuer et al, 2017; Kavenski et al, 2009; Lary et al 2016). Such predictions may be used to derive causalities  
495 or may drive the creation of new hypotheses. In other words, for a predictive model the ‘unguided’ data analyses come first  
and the interpretation follows (Breiman, 2001b; Schmueli, 2010; Obermeyer and Emanuel, 2016). The RF modelling takes  
advantage of the multi-layer information and is able to handle non-linear and complex relationships between image-derived  
Mn-nodule data and explanatory variables from **hydroacoustics** while being resistant to overfitting (Breiman, 2001a).  
Moreover, the randomization of the input training points in each tree in each run, resulting in a complete different training  
500 dataset each time with mixed points from the entire study area. This random selection and mixing of points, is appropriate  
for clustered data, as it ignores their spatial locations and consequently limits the influence of spatial autocorrelation. **To this**  
**direction several authors** Along these lines, several authors have included the values of latitude/longitude and even the LMI  
values as predictor variables in order to increase the model performance (e.g. Li, 2013; Li et al., 2011b; Li et al., 2013). RF  
has a high operational character due to its relatively simple calibration, which does not request extensive data  
505 preparation/transformation or need for geostatistical assumptions (e.g. stationarity). RF model runs can easily be  
implemented inside various software packages and its increased stability can even allow a small number of iterations to  
compute sufficient results (Cutler et al., 2007; Millard and Richardson, 2015). The examination of the main two tuning  
parameters (*n*tree and *m*try) showed that the model performance can be increased compared to default values. However, the  
largest improvement results from using more training data. In this respect, more photos would potentially improve the RF  
510 performance as no clear threshold was observed. Although the number of 11,276 photos seems to represent a large data set,  
the heterogeneity of the distribution and the occurrence of spatial clusters (patches) in different sizes and the inherent need of  
RF and ML in general for big training datasets (van der Ploeg et al, 2014; Obermeyer and Emanuel, 2016), stresses the need  
for collecting more and well distributed data.

Although the exact reasons for the patchy distribution are not fully understood, the distribution pattern is essential for  
515 planning box corer sampling. A random spatial sampling reduces the possibility of dependence among observations in a  
homogeneously distributed population (Cochran 1977), but it is not appropriate for clustered populations as it cannot  
eliminate autocorrelation between neighboring sample locations that are inside the spatial influence of the underlying  
phenomenon (Legendre and Legendre, 1998). In other words, if two or more box-corers are obtained from the same patch,  
the results will still not be representative for the entire study area. Thus, the deployment of box corers should be executed  
520 only after the acquisition, processing and spatial analysis of bathymetric and optical data. The number of box corers should  
be the maximum feasible, with at least one within each main patch. Moreover, sampling should occur in locations with  
available photos (to enable direct comparison) and locations without photos for a true validation of the RF prediction. In  
other words, the optical data acquisition should be guided by the bathymetric and backscatter seafloor characteristics, and be  
followed by box core sampling that targets all defined ‘seafloor-classes’ by considering direct correlations with the  
525 previously gathered optical and **hydroacoustic** data.

**This ‘a priori’** knowledge of the distribution of the Mn-nodules number and size in such scale can contribute to the biological  
data survey planning, too. Recent studies showed that the abundance and species richness of nodule fauna inside the CCZ is

530 affected by the abundance of Mn-nodules (Amon et al., 2016; Vanreusel et al., 2016) as long as from the size of them as  
well as their size (Veillette et al., 2007). Thus, high priority areas (e.g. these with highest commercial interest) can be  
targeted for sampling based on the results of optic data and RF modelling based on the needs of studies the results of optic  
data and RF modelling can lead the data sampling in high priority areas (e.g. these with highest commercial interest).  
535 Finally, the resource assessment showed that block G77 is a potential mining area with high average Mn-nodules density and  
gentle slopes. While here the threshold of 3° (UNOET, 1987) was used, newer plans for mining machines seem to enable  
operations on steeper slopes (Atmanand and Ramadass, 2017) increasing the total amount of collected Mn-nodules within  
the herein considered area.

## 6. Conclusions

The results of this study show that the acquisition and analysis of optical seafloor data can provide quantitative information  
on the distribution of Mn-nodules. This information can be combined with AUV-based MBES data using RF machine  
learning to compute predictions of Mn-nodule occurrence on small operational scales. Linking such spatial predictions with  
540 sampling based physical Mn-nodule data provides an efficient and effective tool for mapping Mn-nodule abundance.

**Competing interests:** The authors declare that they have no conflict of interest.

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545

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## Appendix A: Methodology

### 3.1 Hydroacoustic Data Acquisition & Post Processing

560 The calculation of the bathymetric derivatives was performed with the SAGA GIS v6.3.0 Morphometry library ([http://www.saga-gis.org/saga\\_tool\\_doc/6.3.0/ta\\_morphometry.html](http://www.saga-gis.org/saga_tool_doc/6.3.0/ta_morphometry.html)).

### 3.4 Spatial Statistics

Global Moran's I and Local Moran's I were performed with the ArcMap™ 10.1 software, using the Spatial Statistic  
565 Toolbox, according to its provided equations. As a null hypothesis, it is assumed that the examined attribute is randomly distributed among the features in the study area. For the optimal conceptualization of spatial relationships, the Inverse Euclidian Distance Method was selected, as it is appropriate for modelling processes with continuous data in which the closer two samples are in space, the more likely they are to interact/influence each other or have been influenced from the same reasons. The distance threshold was set at 50m and the increment analysis was performed with a step of 50m.  
570 Moreover, the spatial weights were standardized in order to minimize any bias that exists due to sampling design (uneven number of neighbors). Apart from the index value, the p-value and z-score are also provided. The Local Moran's I indicates statistically significant clusters and outliers for a 95% confidence level. The high number of observations (>>30) that was used ensures the robustness of the indexes.

### 3.5 RF Predictive modelling (Selection of Predictor Variables)

575 Correlation among the derivatives was checked by Spearman's correlation coefficient ( $\rho$ ). This coefficient was preferred due to the skewed distribution of the values in the derivatives. The majority of the possible pairs is uncorrelated or weakly correlated. Only C vs. TPI\_F and TRI vs. S have a strong correlation. However, they should not be excluded as they express different topographic characteristics and they are not correlated with the remainder of derivatives.

**Table A1.** Spearman's correlation coefficient for each pair of predictor variables

580

	<b>D</b>	<b>S</b>	<b>Pl.C</b>	<b>Pr.C</b>	<b>TPI_B</b>	<b>TPI_M</b>	<b>TPI_F</b>	<b>C</b>	<b>TRI</b>
<b>D</b>									
<b>S</b>	-0.07								
<b>Pl.C</b>	0.06	-0.02							
<b>Pr.C</b>	0.08	-0.01	0.37						
<b>TPI_B</b>	0.76	-0.09	0.13	0.16					
<b>TPI_M</b>	0.36	-0.06	0.20	0.27	0.72				
<b>TPI_F</b>	0.23	-0.05	0.33	0.41	0.47	0.77			
<b>C</b>	-0.30	0.05	-0.25	-0.34	-0.54	-0.79	-0.90		
<b>TRI</b>	-0.10	0.91	-0.02	-0.03	-0.12	-0.06	0.04	0.05	

The 9 training samples with different size were created by the MGET tool: Randomly Split Table into **training and testing records**. The spatial randomness of the procedure, combined with the many available data resulted in training samples with similar descriptive statistics.

585 **Table A2.** Descriptive Statistics of different training samples

<b>% Training Sample:</b>	<b>10%</b>	<b>20%</b>	<b>30%</b>	<b>40%</b>	<b>50%</b>	<b>60%</b>	<b>70%</b>	<b>80%</b>	<b>90%</b>
Training set size	1127	2255	3383	4511	5638	6766	7894	9021	10148
Mean	36.5	36.3	36.6	36.6	36.6	36.7	36.6	36.7	36.6
Std. Error	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Std. Deviation	9.3	9.2	9.4	9.2	9.2	9.3	9.3	9.2	9.3
Minimum	7	13	12	13	12	14	7	7	7
Maximum	63	70	72	66	78	78	78	72	78

## Appendix B: Results

### **3.5 RF Predictive modelling (Calibration of the model):**

The descriptive statistics of the performance of each model were used as decision factors for the number of iterations. In all cases, the mean value with very low standard error, the very low standard deviation, range and the 95% confidence interval  
590 indicate a rather stable performance, without the need for further iterations.

**Table B2.** Descriptive statistics of MSR from different training set sizes, after 10 iterations with default settings.

<b>% Training Sample:</b>	<b>10%</b>	<b>20%</b>	<b>30%</b>	<b>40%</b>	<b>50%</b>	<b>60%</b>	<b>70%</b>	<b>80%</b>	<b>90%</b>
Mean	34.8	30.2	26.1	23.3	22.2	21.3	19.7	18.3	18.1
Std. Error	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	34.8	30.3	26.1	23.2	22.2	21.3	19.7	18.3	18.1
Mode	34.7	30.3	26.1	23.2	22.2	21.3	19.7	18.3	18.1
Std. Deviation	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.1
Minimum	34.5	30.1	25.9	23.2	22.1	21.2	19.6	18.2	18.1
Maximum	35.1	30.4	26.3	23.5	22.3	21.3	19.7	18.3	18.1
C.I. (95.0%)	0.1	0.1	0.1	0.1	0.1	0.0	0.0	0.0	0.0

**Table B3.** Descriptive Statistics of MSR from a different number of *ntree* parameter, after 10 iterations with 80% of the sample as training data and *mtry* = 3.

<i>ntree:</i>	100	200	300	400	500	600	700	800	900	1000
Mean	18.8	18.4	18.3	18.3	18.3	18.2	18.2	18.2	18.2	18.2
Std. Error	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	18.8	18.4	18.3	18.3	18.3	18.2	18.2	18.2	18.2	18.2
Mode	18.8	18.4	18.3	18.3	18.3	18.2	18.2	18.2	18.2	18.2
Std. Deviation	0.1	0.1	0.1	0.1	0.0	0.1	0.1	0.1	0.0	0.0
Minimum	18.5	18.4	18.2	18.2	18.2	18.1	18.1	18.1	18.1	18.1
Maximum	18.9	18.5	18.5	18.4	18.3	18.3	18.3	18.3	18.2	18.2
C.I. (95.0%)	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0

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**Table B4.** Descriptive Statistics of MSR from different number of *mtry* parameter, after 10 iterations with 80% of the sample as training data and *ntree* = 600.

<i>mtry:</i>	1	2	3	4	5	6	7
Mean	23.4	19.3	18.2	17.9	17.7	17.6	17.6
Std. Error	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Median	23.4	19.3	18.2	17.9	17.7	17.6	17.6
Mode	23.4	19.3	18.2	17.9	17.7	17.6	17.6
Std. Deviation	0.0	0.1	0.1	0.1	0.0	0.0	0.0
Minimum	23.3	19.1	18.1	17.8	17.6	17.5	17.6
Maximum	23.5	19.4	18.3	17.9	17.7	17.7	17.7
C.I. (95.0%)	0.0	0.1	0.0	0.0	0.0	0.0	0.0

**Table B5.** Descriptive Statistics of MSR for the optimum selected RF model, after 30 iterations with 80% of the sample as training data, *ntree* = 600, and *mtry* = 6.

	Mean	Std. Error	Median	Mode	Std. Deviation	Minimum	Maximum	C.I. (95%)
<b>Optimum RF</b>	17.6	0.0	17.6	17.6	0.0	17.5	17.7	0.0

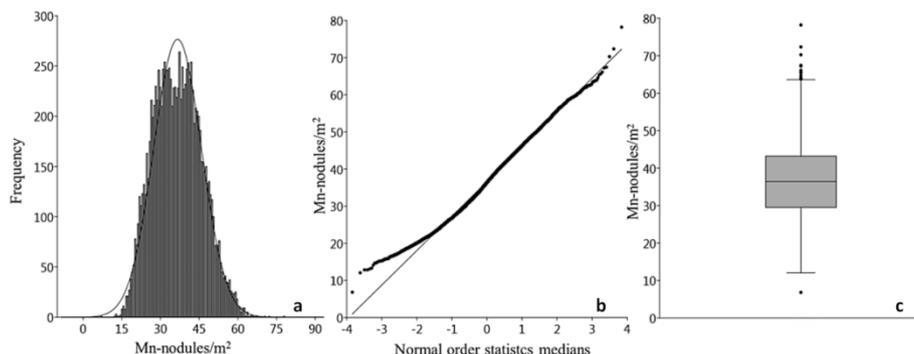
600

**Table B6.** Descriptive statistics of validation measures for the optimum RF model, after 30 iterations with 80% of the sample as training data, *ntree* = 600, and *mtry* = 6 .

<b>RF Importance:</b>	<b>Depth</b>	<b>TPI_B</b>	<b>TPI_M</b>	<b>TRI</b>	<b>TPI_F</b>	<b>C</b>	<b>S</b>	<b>Pl.C</b>	<b>Pr.C</b>
Mean	80.1	63.6	46.7	36.1	24.5	19.7	12.0	2.6	2.4
Std. Error	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0
Median	80.1	63.5	46.7	36.1	19.7	19.7	11.9	2.6	2.4
Mode	80.1	63.3	46.9	36.1	19.8	19.8	11.9	2.6	2.4
Std. Deviation	0.4	0.6	0.6	0.2	0.2	0.2	0.2	0.0	0.0
Minimum	79.1	62.6	45.0	35.7	19.2	19.2	11.7	2.5	2.3
Maximum	80.8	64.9	47.7	36.4	20.1	20.1	12.4	2.6	2.5
C.I. (95.0%)	0.1	0.2	0.2	0.1	0.1	0.1	0.1	0.0	0.0

#### 4.1 Data Exploration:

The histogram of Mn-nodules/m<sup>2</sup> (Figure B1) shows a good fit with the superimposed theoretical normal curve, with most of the frequency counts in the middle and the counts die out in the tails with the shape of the distribution being rather symmetrical. This fact is approved supported by the equal mean and median and the slightly different mode (Table B6). Similarly, the visual inspection of the probability plot (Figure B1) shows a good match as a linear pattern is observed for the greatest part, with slight deviation existing only in the outer parts of the curve. According to the boxplot, there are only 21 mild outliers (according to Hoaglin et al., 1986; Dawson, 2011), which correspond to the 0.18% of the total observation. This percentage is smaller than the 0.8% threshold that has been suggested for normal disturbed data (Dawson, 2011). The small values for skewness and kurtosis combined with the large sample size further support the normal distributed pattern of the data (Table B6). Especially for large data samples, measurements of skewness and kurtosis combined with the visual inspection of histogram and probability plot are recommended ways of examining normality of data (D' Agostino et al., 1990; Yaziki and Yolacan, 2007; Field, 2009; Ghasemi and Zahediasl, 2012; Kim, 2013).



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**Figure B1** a) Histogram of Mn-nodules/m<sup>2</sup> with the superimposed normal curve. b) The normal probability plot of Mn-nodules/m<sup>2</sup>. c) The box plot of Mn-nodules/m<sup>2</sup>.

**Table B6.** The descriptive statistics of the number of Mn-nodules/m<sup>2</sup>.

	Mean	5% Trim. Mean	Median	Mode	SD	Min.	Max.	Skew.	Kurtosis
Mn-nodules/m <sup>2</sup>	36.6	36.4	36.4	39	9.2	6.8	78.2	0.1	-0.4

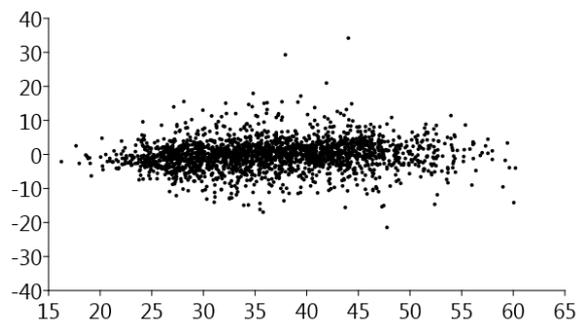
A potential linear correlation between depth, bathymetric derivatives, and number of Mn-nodules/m<sup>2</sup> was investigated using the Spearman's rank correlation coefficient ( $\rho$ ) because of the skewed distribution and presence of extreme values in the depth and bathymetric derivative values (Mukaka, 2012).

**Table B7.** The Spearman's rank correlation coefficient between Mn-nodules/m<sup>2</sup> depth, and bathymetric derivatives

Depth	Slope	TRI	Pl.C	Pr.C	TPI_B	TPI_M	TPI_F	Con.
0.38	0.08	0.07	0.03	0.04	0.29	0.24	0.05	-0.14

#### 4.3.2 Selection, application and external validation of the optimal model

Despite the fact that RF is a full non-parametric technique and there is no need for the residuals to follow specific assumptions (Breiman, 2001a), the examination of them can provide an in-depth look into its performance characteristics. The scatterplot of residuals against predicted values shows a random pattern, which is also confirmed by the low values of Pearson, Spearman, and R<sup>2</sup> coefficients between predicted values and residuals (Figure B1a and Table B6). Moreover, the residuals tend to cluster towards the middle of the plot without being systematically high or low, and having zero mean value (Figure B1 and Table B7). Their constant variance (homoscedasticity) implies that the distribution of error has the same range for almost all fitted values. Indeed, 99.3% of the residuals are inside the range  $\pm 15$  and mainly the 81.2% inside the range  $\pm 5$  (Table B8). The presence of outliers is very limited without affecting the main statistical characteristics of residuals (Table B7) indicating that the model adequately fits the overwhelming majority of the observations (>2165) and only random variation (that exists in any real natural phenomenon) or noise can occur.



635 **Figure B2.** Scatterplot between residuals and predicted values.

**Table B8.** Pearson, Spearman, and R<sup>2</sup> correlation coefficients between residuals and predicted values.

	Pearson	Spearman	R <sup>2</sup>
Correlation of residuals and predicted values	0.1	0.2	0.0

**Table B9.** Main descriptive statistics of residuals and 5% trimmed residuals

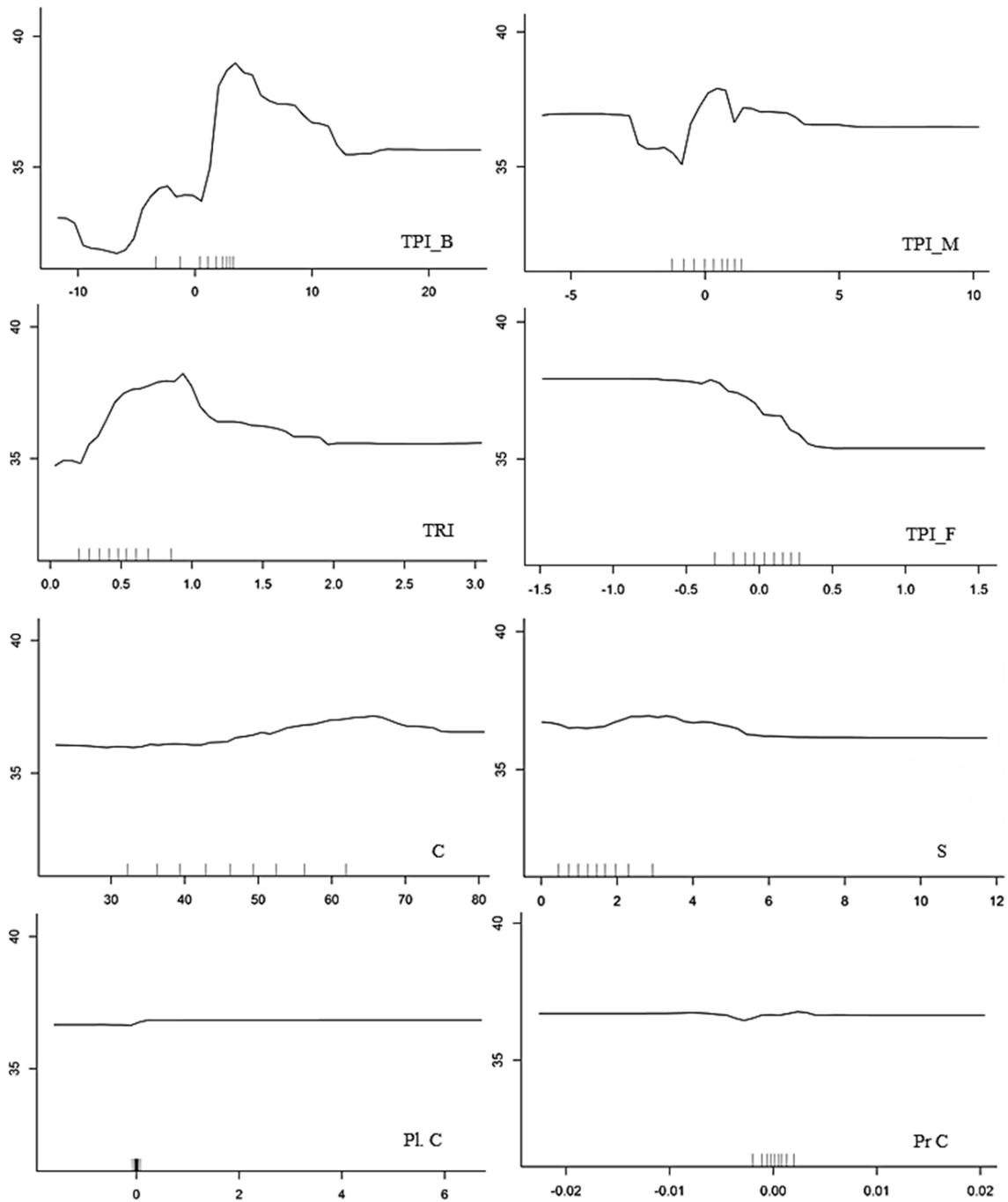
	Mean	Std. Error	Median	Mode	Std. Deviation
Residuals	-0.2	0.1	-0.2	0.6	4.4
5% Trimmed Residuals	-0.2	0.1	-0.2	0.6	2.9

**Table B10.** Residuals range

Residuals Range	±20	±15	±10	±5
% of Residuals	99.8	99.3	96.1	81.2

640 4.3.4 RF importance

The production of the RF partial dependence plots, show the non-linear character between the Mn-nodules/m<sup>2</sup> and the bathymetric derivatives.



645 **Figure B2.** Partial dependence plots for each of the predictor variables. The y axis represent the number of Mn-nodules/m<sup>2</sup> and the x axis the values of each predictor variable (depth derivatives). The ticks inside the graphs indicate the deciles of the data.

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