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Predicting organic enrichment under marine finfish farms in southwestern New Brunswick, Bay of Fundy: Comparisons of model predictions with results from spatially-intensive sediment sulfide sampling

Prévision de l'enrichissement organique dans les sites d'élevage de poissons marins dans la baie de Fundy, au sud-ouest du Nouveau-Brunswick : comparaisons des modèles de prévisions avec des résultats tirés des d'échantillonnage spatialement-intensif de sulfures dans les sédiments

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ABSTRACT

The DEPOMOD (version 2) model was used to predict the rate of organic enrichment of sediments under five operating salmon farms in the southwestern New Brunswick (SWNB) portion of the Bay of Fundy. The model predictions were compared to observed sediment sulfide concentrations at the same farms. DEPOMOD incorporates current speed and direction, feed rates per cage, and bathymetry to predict the spatial distribution of carbon deposition rates on the seafloor under fish farms. Using DEPOMOD, higher current speeds resulted in predictions of larger areas of moderate impact, but smaller areas of highest impact and lower maximum deposition rates. Except where current speeds were low, DEPOMOD's resuspension module appeared to overestimate the amount of particle transport caused by resuspension, and, therefore, underestimated the spatial extent and intensity of seafloor impacts; this suggests that the threshold current speed for resuspension (approximately 9.5 cm s^{-1}) may be inappropriate for SWNB. Comparisons among sites between DEPOMOD predictions (with resuspension off) of the extent of seafloor area with elevated impacts and observed seafloor areas with elevated sulfide concentrations produced variable results. Comparisons among sites between DEPOMOD predictions of the maximum carbon deposition rates (with resuspension off) and the maximum observed sediment sulfide concentrations showed no relationship. The relationships between sediment sulfide concentration at individual sample locations and DEPOMOD predicted carbon deposition rates (with resuspension off) at the same locations showed wide variability at all study sites. However, where DEPOMOD predicted low deposition rates, sulfide concentrations were usually low, but where DEPOMOD predicted high deposition rates, sulfide concentrations ranged from low to high. A simple model, based on an average feed pellet sinking rate, median mid-depth current speeds, and the average site depth, was also tested to predict the spatial extent of impacted seafloor (but not the intensity or precise spatial distribution of impacts). The spatial extent of impacted seafloor predicted by the simple model showed relatively good agreement with the spatial extent of impacted seafloor predicted by DEPOMOD (with resuspension off). Possible sources of uncertainty in the DEPOMOD predictions are discussed.

RÉSUMÉ

Le modèle DEPOMOD (version 2) a été utilisé pour prévoir le taux d'enrichissement organique des sédiments sous cinq exploitations salmonicoles en activité dans la région sud-ouest du Nouveau-Brunswick de la baie de Fundy. Les prévisions du modèle ont été comparées aux concentrations de sulfures dans les sédiments observées dans les mêmes exploitations. Le modèle DEPOMOD intègre la vitesse et l'orientation des courants, le taux d'alimentation par cage et la bathymétrie pour prévoir la répartition spatiale du taux de dépôt de carbone sur le fond marin sous les exploitations aquacoles. En utilisant le modèle DEPOMOD, des vitesses de courant plus rapides ont donné lieu à des prévisions d'impact modéré dans les secteurs plus importants, à des prévisions d'impact plus élevé et à des taux de dépôt maximal plus faibles dans les secteurs plus restreints. Sauf lorsque les vitesses de courant étaient faibles, le module de remise en suspension du modèle DEPOMOD semblait surestimer le transport de particules engendré par la remise en suspension et, par conséquent, il semblait sous-estimer l'étendue spatiale et l'intensité des répercussions sur le fond marin. Cela semble indiquer que le seuil lié à la vitesse du courant de remise en suspension (environ 9,5 cm s^{-1}) peut être inapproprié pour le sud-ouest du Nouveau-Brunswick. Des comparaisons parmi les sites entre les prévisions du modèle DEPOMOD (avec remise en suspension désactivée) relatives à l'étendue des aires du fond marin ayant des impacts élevés et les aires du fond marin observé ayant des concentrations élevées de sulfure ont donné des résultats variables. Des comparaisons parmi les sites entre les prévisions du modèle DEPOMOD de taux de dépôt de carbone maximal (avec remise en suspension désactivée) et les concentrations maximales de sulfures dans les sédiments n'ont démontré aucune relation. Les relations entre les concentrations de sulfures dans les sédiments à des lieux de prélèvement d'échantillons individuels et les taux de dépôt de carbone prévus par le modèle DEPOMOD (avec remise en suspension désactivée) aux mêmes endroits ont montré une grande variété dans tous les sites d'étude. Cependant, lorsque le modèle DEPOMOD avait prévu de faibles taux de dépôt, les concentrations de sulfides étaient habituellement faibles, mais lorsque le modèle DEPOMOD avait prévu des taux de dépôt élevés, les concentrations de sulfides variaient de faibles à élevées. Un modèle simple, établi selon un taux d'immersion moyen des aliments granulés, les vitesses de courant à mi-profondeur médians et la profondeur moyenne des sites, a également été mis à l'essai afin de prévoir l'étendue spatiale du fond marin touché (mais non l'intensité ou la répartition spatiale précise des répercussions). L'étendue spatiale du fond marin touché prévue par le modèle simple a affiché une harmonie relativement bonne avec l'étendue spatiale du fond marin touché prévue par le modèle DEPOMOD (avec remise en suspension désactivée). Des sources d'incertitude probables dans les prévisions du modèle DEPOMOD font l'objet de discussions.

INTRODUCTION

Marine fish farming began in the southwestern New Brunswick (SWNB) area of the Bay of Fundy in 1978. There are now more than 90 licensed farms. Of these, 54 were actively farming Atlantic salmon (*Salmo salar*) and four were farming non-salmonid finfish in 2010. All farms with approvals to operate must conduct annual benthic monitoring of sediments, as part of the Environmental Management Program (EMP) for the marine finfish cage aquaculture industry in New Brunswick, managed by the New Brunswick Department of Environment and Local Government (NBDELG). The EMP (NBDENV 2006) requires monitoring of sediment sulfide concentrations at farms between 1 August and 31 October each year (Tier 1 monitoring). The sulfur cycle and its relationship to organic matter deposition is reviewed in Hargrave et al. (2008). At each farm, triplicate samples must be taken from at least one location for each 100,000 fish on site, with a minimum of two sampling locations per farm; details on determining the sampling locations are given in NBDENV (2010). The average sulfide concentrations of all samples collected at a farm are used to classify the farm within Oxic, Hypoxic, and Anoxic categories according to Table 1. Farms are not assessed based on changes in sulfide concentrations relative to background levels. Data collected at reference sites (away from operating farms and other pollution sources) (Hargrave et al. 1995, 1997; Page et al. 2011) and unpublished data collected since 2000 at several finfish farm sites prior to the start of operations, indicate that background sediment sulfide concentrations in f are generally <300 µM (in the Oxic A category).

It has been suggested that models could be used to predict the suitability of proposed farm sites. One model that has been used to predict organic deposition rates at salmon farms is DEPOMOD (Cromey et al. 2000, 2002), which was developed in Scotland. DEPOMOD predicts carbon deposition rates at fish farms, based on the feed rates in each cage, current velocities at the site, and bathymetry. This model has been used to predict carbon deposition rates at salmon farms in British Columbia (Chamberlain et al. 2005; Chamberlain and Stucchi 2007). Brooks (2007) reported that DEPOMOD predictions showed similar patterns to actual sediment data collected near salmon farms in British Columbia. Department of Fisheries and Ocean's (DFO's) Habitat Management Division has shown interest in using DEPOMOD to predict carbon deposition rates at proposed fish farms in Atlantic Canada.

The objectives of this study were:

- To determine the effectiveness of DEPOMOD (i.e. how precise is the model when compared to post impact monitoring) in predicting:

    (a) the intensity of organic enrichment from marine finfish aquaculture sites in the Maritimes Region,
    (b) the geographic location of impact from marine finfish aquaculture sites in the Maritimes Region, and
    (c) the magnitude of area (in m^2) of impact from marine finfish aquaculture sites in the Maritimes Region.

- To identify any alternative model(s) that would more accurately predict organic enrichment intensity, magnitude and area of impact from marine finfish aquaculture sites in the Maritimes Region.

To achieve these objectives, DEPOMOD was used to predict organic carbon deposition rates at five operating salmon farms in SWNB. The model outputs included the intensity (the rate of carbon deposition), the spatial distribution of carbon deposition, and the magnitude of the predicted area with elevated carbon deposition rates. For each farm, DEPOMOD was run using current velocities from two or three locations in the immediate vicinity of the farm; this allowed examination of the effects of spatial variability in current velocity on the model predictions. DEPOMOD predictions were compared to observed levels of impacts at each farm. Observed levels of impacts were based on spatially-intensive sediment sulfide sampling at each farm. Sediment sulfide concentration was used to measure actual impacts, because this is the parameter used for regulatory purposes in SWNB (NBDENV 2006). Because DEPOMOD predictions and observed impacts involve two different parameters (carbon deposition rate versus sediment sulfide concentration), exact comparisons are not possible. However, it has been observed that there is a positive relationship between sulfide concentrations in surface sediments and organic matter sedimentation (Holmer et al. 2005; Hargrave et al. 2008; Hargrave 2010).

The area of impacted seafloor (but not the intensity) was also predicted using a simpler model, which used average water depths and current speeds at each site as its main data inputs. The predictions from the simple model were compared with DEPOMOD predictions and the observed sediment sulfide concentration data. Some preliminary results from this study have been previously reported (Page et al. 2007, 2009).

METHODS

STUDY SITES

The study sites were five operating salmon farms located in the SWNB portion of the Bay of Fundy. Sediment sampling was conducted at sites A, C, and D as part of a study on the characterization of the spatial pattern of sediment sulfide conditions under salmon farms (Chang et al. 2011), while sites G and H were subject to EMP Tier 2 sediment sampling (NBDENV 2010). All five farms grew Atlantic salmon in net cages suspended from floating, circular, plastic collars. Cage locations were estimated based on sediment sampling locations, Global Positioning System (GPS) readings, aerial photos, and/or farm site plans. Site H was an integrated multi-trophic aquaculture (IMTA) site, also growing seaweeds and mussels. Information on stocking, fish biomass at the time of sediment sampling, maximum biomass, and harvesting times were obtained from production plans submitted by farm operators to NBDENV or directly from the farm operators. Seafloor depths (averages of depth sounding data within the cage arrays, in metres below Chart Datum) and mean tidal heights (metres above Chart Datum) at the study sites were based on Canadian Hydrographic Service (CHS) data. As a measure of the degree of exposure of the sites to wind, an index developed by Peterson et al. (2001) was used. This exposure index is calculated from monthly wind velocity data collected at the Saint John, NB airport over one year (using 1995 data) and the distance of open water from each site to the nearest land (to a maximum of 5 km) in 16 compass directions.

CURRENT VELOCITY MEASUREMENT

At sites A, C, D, and H, current velocities were measured using Teledyne RD Instruments Workhorse Sentinel Acoustic Doppler Current Profilers (ADCPs). The ADCPs were moored about one meter (m) above the seafloor, at two or three locations in the vicinity of each farm. The ADCPs measured current speed and direction at 1 m depth intervals throughout the water column. From the data record, current velocity data were extracted for three depth layers: near-surface, mid-depth, and near-bottom. The near-surface layer was a constant depth below the water surface (2.5–3.5 m, depending on the deployment) and the near-bottom layer was a constant distance above the seafloor (3.6–4.7 m, depending on the deployment). The mid-depth layer was a constant distance above the seafloor, approximately mid-way between the near-surface and near-bottom layers. At site G, currents were measured using InterOcean S4 current meters, moored at two locations, 6 m above the seafloor. The S4 meters measured current velocities only at the deployment depth.

SIMPLE MODEL

The simple model assumed that current speeds were equally distributed in all horizontal directions and also did not vary vertically. This model used data on mid-depth current speeds, average water column depth (under the cage array), cage sizes and locations, and average sinking rates for particles released from the farm. The sinking rates used were the default average values used in DEPOMOD: 11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces. Areas of deposition were estimated as circles around each cage, with radii (extending from the cage edge) equal to the horizontal displacements of particles upon hitting the seafloor. The horizontal displacement of a particle was calculated as the horizontal current speed multiplied by the sinking time. The horizontal displacements were calculated using the median and maximum current speeds (at mid-depth), for both feed pellets and feces. The resulting areas of particle displacement were estimated using the MapInfo (version 8.0) buffer tool. This simple model was intended only for providing a rough estimate of the overall area of impact, assuming no resuspension; it could not predict spatial heterogeneity in sediment deposition under farms. Simple model predictions of the areas of sediment impacts on the seafloor using maximum current speeds were assumed to be overestimates, since maximum currents occur only rarely.

DEPOMOD

DEPOMOD version 2 (Cromey et al. 2000, 2002) was used to predict the organic carbon deposition rate on the seafloor in the vicinity of each farm. The Grid Generation module is used to define the model prediction area, which is determined by the sizes of the grid cells and the numbers of grid cells. The module allows the creation of a fine scale minor grid in the immediate vicinity of the farm and a larger scale major grid for areas further away. A fine-scale grid was used throughout the prediction domain, so the sizes of the grid cells were the same for the major and minor grids. A grid cell dimensions of 10 × 10 m was used at all farms except site H, where grid cells of 20 × 20 m were used due to the larger size of that farm. At all farms, the major grid was 99 × 99 cells, and the minor grid was 98 × 98 cells. The resulting domain size was approximately 1,000 × 1,000 m (except 2,000 × 2,000 m at site H). Bathymetry data at the centre of each grid cell must be provided for the Grid Generation module. Bathymetry data (meters below chart datum) were obtained from CHS field sheets. Bathymetry estimates for the grid cell centres were linearly interpolated from the CHS data. The location of the centre of each fish cage must also be entered in this module. The grid files that are produced by the Grid Generation module are then used in the Particle Tracking module.

The Particle Tracking module uses the output from the Grid Generation module to predict where particles released from the cages will land on the seafloor. The Particle Tracking module was used to predict carbon deposition, assuming continuous release of food; this is the typical DEPOMOD scenario used to predict effects of new and existing farms (Cromey et al. 2000). The Particle Tracking module has two main parts: fish farm characteristics and the particle tracking model set-up. Fish farm characteristics include particle information (water content, digestibility, percentage wasted, carbon content, and settling velocity of feed particles; carbon content and settling velocity of feces) and cage set-up (cage diameter and depth; feed input per cage). The values used for the particle information were values recommended when using DEPOMOD in the DFO Pacific Region (Stucchi and Chamberlain, unpublished data; see Table 2). DEPOMOD releases particles from random starting positions within each cage, so data on the cage dimensions must be entered. The cage diameters were obtained from site plans, but the depths of the net cages (from the water surface to the bottom of the net cage) were not known, so we used a net cage depth of 10 m, which is typical for salmon cages in SWNB. Feed rates per cage were obtained from the farm operators. At all sites, the feed input used in the model was the average daily feed rate per cage during a four to five week period which included the sediment sampling date. At site G, where feed rates were very low at the time of sediment sampling (September 2010), the Particle Tracking module was also run using higher feed rates from earlier in the year (July 2010). The particle tracking model set up includes current velocity data input, a turbulence model, and a particle trajectory model. Current velocity data were obtained from two or three current meter deployments of 35-97 day duration in the immediate vicinity of each farm. Hourly water current velocity records were extracted for three depth layers (near-surface, mid-depth, and near-bottom), except at site G, where data from only one depth were available. For the turbulence model, the random walk model was selected, with default values for the dispersion coefficients. For the particle trajectory model, default values were used. Another input required in this module is the mean tidal height (meters above chart datum). This is used to estimate the average depth of the water column, which is then used to calculate the depth that particles must fall to reach the seafloor; DEPOMOD assumes a temporally constant water depth, based on the mean tidal height. The cage set up allows a maximum of 30 cages per run; therefore, at site H, which had 33 cages (in three rows), the DEPOMOD was run twice (using the same domain and grid), once with two rows of cages, and then with the third row, and the carbon deposition estimates per grid cell from the two model runs were summed.

The Resuspension module was then run to calculate the predicted carbon deposition rate in each grid cell. The Resuspension module was first run with resuspension turned off, and then with resuspension on. The resuspension parameters in DEPOMOD are fixed: the critical shear stress for resuspension is 0.0179 N m^{-2} (approximately 9.5 cm s^{-1} near bottom current speed); the critical shear stress for deposition is 0.004 N m^{-2} (approximately 4.5 cm s^{-1} near bottom current speed); and the erodibility constant is 7×10^{-7} kg m^{-2} s^{-1}. Resuspension only affects unconsolidated particles; the default consolidation time of 4 days was used.

The model was run for two loops of the current meter record, as recommended in the DEPOMOD manual in order to achieve a steady state solution (Cromey et al. 2000). The output selected was carbon flux, in g m^{-2} yr^{-1} (at the centre of each grid cell). The carbon flux values were then converted to g m^{-2} d^{-1}.

Contour plots of the predicted carbon deposition rates at the centre of each grid cell were produced using MapInfo Vertical Mapper (version 3.1.1) software. The interpolation technique was Rectangular; the contouring software user guide (MapInfo Corporation 2005) recommends this technique when data points are evenly distributed, as in DEPOMOD outputs. Default values (calculated by the contouring software) for Cell size and Search radius were used. The contour intervals were defined by the carbon deposition rates corresponding to the sediment classifications in Table 1. Deposition rates <0.3 g C m^{-2} d^{-1} were considered to be background levels; this was the carbon deposition rate at control sites in SWNB reported by Hargrave (1994).

Mass balance calculations compared the DEPOMOD predicted total rate of waste production by a farm (waste feed and feces) with the predicted rate of waste deposition on the seafloor within the model domain. The total rate of waste production was calculated as the total feed rate (all cages combined) multiplied by the rate of waste production per unit of feed. The waste production rate per unit of feed was calculated by DEPOMOD based on the input feed characteristics. Using the feed characteristics in Table 2, the model estimated the waste production rate per unit of feed (waste feed plus feces) to be 0.044 kg C per kg feed. The total rate of waste deposition within the model domain was calculated as the sum of the predicted waste deposition rates in all grid cells. The waste deposition rate in each grid cell was calculated as the estimated deposition rate at each grid point (in g C m^{-2} d^{-1}) multiplied by the size of each grid cell (in m^2).

SEDIMENT SULFIDE CONCENTRATION DATA

Sediment sampling was conducted at all five sites during July-September. At site A, sampling was also conducted in the spring following the fall sampling. At sites A, C, and D, the sediment samples were collected within the cage arrays and up to 100 m or more away, using Hunter-Simpson grab samplers deployed from a boat. The use of surface-deployed grabs meant that samples could not be taken directly under cages, but many samples were taken at cage edges. Details on the sampling at these sites are reported in Chang et al. (2011). Grab samples were 0.096 m^2 at site A in 2005 and 0.024 m^2 at site A in May 2006 and at sites C and D. Triplicate 5 ml subsamples were taken from the top 2 cm of the sediment surface of each grab sample. Sediment samples at sites G and H were taken as part of the EMP Tier 2 sampling (NBDENV 2010); triplicate core samples were taken by divers at several locations within, but not outside of the cage arrays. Because of diver safety concerns, samples could not be collected directly under cages, but many samples were collected at cage edges. Core samples were collected using core tubes approximately 30 cm long by 5 cm in diameter. One 5 ml subsample was taken from the top 2 cm of the sediment surface of each core sample. Sulfide concentrations (μM) in all sediment samples were measured using an Orion 9616BN silver/sulfide electrode, connected to an Accumet AP25 meter, following the method described by Wildish et al. (1999, 2004) and NBDENV (2010). All samples were stored in ice and analyzed within 2 days of sample collection. Contour plots of the sediment sulfide concentrations (means of triplicate subsamples at each sampling location) were produced using MapInfo Vertical Mapper. The interpolation technique was Natural Neighbor (Simple); this technique appeared to be a reasonable choice for the distributions of sediment sampling points, based on recommendations in the software user guide (MapInfo Corporation 2005). Default values (calculated by the contouring software) were used for Cell size and Aggregation distance. The Surface Solution Type used was Smoothed, without overshoot (the default choice). Baseline sediment sulfide concentrations (from before the farm began operating) were available for site A. At the other sites, sediment sulfide concentrations were available from reference sites located near the study sites (Table 3). These data indicate that baseline and reference site sediment sulfide concentrations in SWNB are ≤300 μM.

COMPARISON OF DEPOMOD PREDICTIONS AND SEDIMENT SULFIDE DATA

To compare the DEPOMOD predictions of carbon deposition with the sediment sulfide data, we used the nomogram for benthic organic enrichment zonation in Hargrave et al. (2008), which was based on data collected by Chamberlain and Stucchi (2007). The corresponding values of sediment sulfide concentrations and carbon deposition rates in each category are shown in Table 1; the Hypoxic B category in the nomogram was subdivided evenly into Hypoxic B and C categories to match the site classifications used in the EMP (Table 1). The areas (m^2) within each category in the contour plots of sediment sulfide concentrations were compared to the areas in contour plots of DEPOMOD predictions of carbon deposition rates at the same site. Areas of elevated seafloor impacts were defined using the threshold of Hypoxic B conditions, equivalent to a carbon deposition rate of 5 g C m^{-2} d^{-1} or a sediment sulfide concentration of 3,000 μM (see Table 1). The relationship between the intensity of observed and predicted impacts was examined in two ways: 1) for each farm, the maximum observed sediment sulfide concentration (from means of triplicate subsamples at each sampling location) was compared with the maximum DEPOMOD predicted carbon deposition rate in each model run; 2) for each sediment sampling point (at each farm), the observed sulfide concentration was compared with the DEPOMOD predicted carbon deposition rate in the corresponding model grid cell.

RESULTS

GENERAL INFORMATION

Data on wind exposure, water depths, cage types, stocking numbers, salmon biomass, and feed rates at the study sites are presented in Tables 4-8.

SITE A

Site A (Fig. 1) had 14 cages, arranged in two rows of seven cages each, at the time of sediment sampling (September 2005 and May 2006). Thirteen cages were 100 m circumference cages and one was a 50 m circumference cage. The average distance between CHS depth soundings within the DEPOMOD domain was 91 m (range: 51–150 m). Water depths under the cage array were fairly even, ranging from about 15–17 m (below Chart Datum), with the shallowest area at the northern end. This was the most exposed of the study sites (Table 5). The farm was stocked in the fall of 2004 (Table 6). Sediment sampling was conducted on 12 September 2005 (about a year after stocking) and again on 24 May 2006 (about 1-2 months prior to the date of maximum fish biomass and the start of harvesting; see Table 7). In the month of the first sediment sampling in September 2005, the fish biomass per cage varied widely, ranging from a low of 18 t in the one 50 m circumference cage, to 23–76 t in the thirteen 100 m circumference cages. The average daily feed rate at site A in September 2005 also varied widely among cages, ranging from 203 kg d^{-1} in the 50 m circumference cage, to 363–1,045 kg d^{-1} in the 100 m circumference cages (Table 8). The overall feed rate in September 2005 was near the peak rate for that year. The feed rate declined during the winter in late 2005 and early 2006, and then increased in the spring of 2006 (Fig. 2). In the month of the second sediment sampling, May 2006, the overall feed rate was higher than in the previous fall, and was near the peak rate for the year. The fish biomass per cage varied widely in May 2006, ranging from 31 t in the 50 m circumference cage to 77–173 t in the 100 m circumference cages. The average daily feed rate at site A in May 2006 also varied widely, ranging from 180 kg d^{-1} in the 50 m circumference cage, to 615–1,113 kg d^{-1} in the 100 m circumference cages (Table 8).

Two of the current meter deployments (CM329 and CM330) were concurrent with the September 2005 sediment sampling, and the other deployment (CM324) was in the previous winter (Table 9). The locations of these deployments are shown in Fig. 1. Current speeds at site A were moderate, with median speeds ranging from 7.0–9.6 cm s^{-1}, and maximum speeds ranging from 35.6–44.3 cm s^{-1} (Table 10). Within each current meter deployment, the current speeds and directions did not show large differences between depths. There were, however, differences in current velocities between the three deployments, although current directions were mainly away from the nearest shore in all three cases (Table 10, Fig. 3). For deployment CM324, speeds were relatively low and the direction was mainly to the southwest, but also to the west. For deployment CM329, speeds were higher and the direction was mainly to the northwest, but also to the west. For deployment CM330, speeds were highest and the direction was mainly to the northwest, but also to the southeast. In all three deployments, the percentage of near-bottom current speeds above the DEPOMOD threshold for resuspension (9.5 cm s^{-1}) was about 50% (Table 10).

Using the average sinking rates used in DEPOMOD (11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces), the time required for particles to sink from the mean sea level to the seafloor (20.2 m) was 3.1 min for feed pellets and 10.5 min for feces. Simple model predictions showed relatively small differences between the estimates from the three current meter deployments (Table 11, Fig. 4); the area of impact was lowest using data from CM324 (which had the lowest mid-depth current speed), while the areas of impact using data from the other two current meters were similar.

When DEPOMOD was run at site A with resuspension off and average daily feed rates per cage during September 2005, all of the waste material remained within the model domain (Table 12). There was considerable spatial heterogeneity in seafloor deposition, with highest deposition under the cages receiving the most feed. The predictions were similar using the three current meter deployments; the seafloor area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} ranged from 21,400–26,700 m^2, and the area with anoxic rates (>10 g C m^{-2} d^{-1}) ranged from 2,400–4,000 m^2 (Table 13, Fig. 5). The area with elevated impacts was largest using current velocities from CM324 (which had the lowest current speeds), and the area with the highest impacts (anoxic) was also largest with CM324. With resuspension on, almost all of the waste material was transported outside the model domain (Table 12), and there was no seafloor with carbon deposition rates >5 g C m^{-2} d^{-1} (Table 13, Fig. 6).

When DEPOMOD was run at site A with resuspension off and average daily feed rates per cage during May 2006, all of the waste material remained within the model domain (Table 12), but there were greater impacts compared to when September 2005 feed rates were used, due to the higher feed rates in May 2006. With resuspension off, the seafloor area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} at site A in May 2006 ranged from 32,300–32,900 m^2 and the area with anoxic rates (>10 g C m^{-2} d^{-1}) ranged from 11,800–18,700 m^2 (Table 14, Fig. 7). The area with deposition rates >5 g C m^{-2} d^{-1} was largest using current velocity data from CM329, while the area with highest predicted impacts was largest with CM324. With resuspension on, almost all of the waste material was transported outside the model domain (Table 12); there was no seafloor with carbon deposition rates >5 g C m^{-2} d^{-1} (Table 14, Fig. 8).

The maximum predicted carbon deposition rates were similar using data from the three current meter deployments with resuspension off, ranging from 20.4–25.5 g C m^{-2} d^{-1} (in the Anoxic category) using September 2005 feed rates, and slightly higher, ranging from 22.5–27.7 g C m^{-2} d^{-1} using May 2006 feed rates (Table 15); in both years the highest rates were with CM324. With resuspension on, the maximum predicted carbon deposition rates were much lower: 1.9–4.1 g C m^{-2} d^{-1} (Oxic B to Hypoxic A) using September 2005 feed rates and 3.1–4.9 g C m^{-2} d^{-1} (Oxic A to Hypoxic A) using May 2006 feed rates (Table 15); in both years the highest rates were with CM329.

Sediment sulfide data were collected from triplicate samples at 57 locations within the cage array and extending to about 120 m from the cage array on 22 September 2005, and from all but two of the same locations on 24 May 2006 (see Chang et al. 2011 for details). Sediment sulfide concentrations showed patchy distributions on both sampling dates. On 22 September 2005, there were some patches of anoxic sediments, totalling 8,000 m^2, and a total of 32,200 m^2 of Hypoxic B or higher sediments (Table 16, Fig. 9). Some of the anoxic patches were close to the cages with the highest feed rates, but others were near cages with relatively low feed rates. Some of the anoxic patches extended beyond the edge of the cage array. On 24 May 2006, the sulfide concentrations were much lower (Table 16, Fig. 9): there were no areas of anoxic sediments and a total of 17,000 m^2 of Hypoxic B or higher sediments; the highest sulfide areas were in the Hypoxic C category (1,800 m^2). For both dates, the areas with elevated sulfide concentrations may be somewhat underestimated because elevated sulfide concentrations were found at some of the westernmost sample locations, suggesting that impacted conditions extended beyond the sampling grid. The maximum observed sediment sulfide concentration (from means of triplicate subsamples) in September 2005 was in the anoxic category, and was about double the highest concentration in May 2006, in the Hypoxic C category (Table 15).

SITE C

Site C (Fig. 10) had fifteen 100 m circumference cages, in three rows of five cages each, at the time of sediment sampling (September 2006). The average distance between CHS depth soundings within the DEPOMOD domain was 23 m (range: 8–47 m). Water depths under the cage array ranged from 11–28 m (below Chart Datum), with the shallowest area at the northwestern corner of the site and the deepest area along the southern edge. The site had a moderate exposure index (Table 5). The farm was stocked in the spring of 2005 (Table 6). Sediment sampling was conducted on 12 September 2006, during the month of maximum feeding (Fig. 11), about two months prior to the start of harvesting (Table 7). In the month of the sediment sampling, September 2006, the fish biomass per cage was fairly even, ranging from 104–146 t. The average daily feed rate in this month was relatively similar among cages, ranging from 850–1,010 kg d^{-1} (Table 8).

Neither of the two current meter deployments (Fig. 10) were concurrent with the September 2006 sediment sampling; CM318 was in summer-fall 2003 and CM379 was in summer 2009 (Table 17). Current speeds were moderate in both current meter deployments, but with slightly higher speeds at CM318 (Table 18). Current direction was mainly to the southwest and northeast, roughly parallel to the shoreline, in both deployments (Fig. 12). For deployment CM318, currents were stronger to the southwest near the surface, stronger to the northeast near the bottom, and fairly equal in both directions at mid-depth. For deployment CM379, current velocities were similar between depths. The percentage of near-bottom current speeds above the DEPOMOD threshold for resuspension (9.5 cm s^{-1}) was 66% for CM318 and 49% for CM379.

Using the average sinking rates used in DEPOMOD (11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces), the time required for particles to sink from the mean sea level to the seafloor (23.4 m) was 3.5 min for feed pellets and 12.2 min for feces. Simple model predictions of the area of impact were very similar using the two sets of current velocity data (Table 19, Fig. 13).

When DEPOMOD was run at site C with resuspension off and average daily feed rates per cage during September 2006, all of the waste material remained within the model domain (Table 20). The seafloor area with elevated carbon deposition rates, was quite large, relatively evenly distributed under the cage array, and similar for the two current velocity datasets: the area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} was 48,600–50,200 m^2, and the area with predicted carbon deposition rates >10 g C m^{-2} d^{-1} was 20,700–22,400 m^2 (Table 21, Fig. 14). With resuspension on, almost all of the waste material was transported outside the model domain (Table 20); there was very little or no seafloor area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} (Table 21, Fig. 14).

The maximum predicted deposition rates with resuspension off were 17.9 g C m^{-2} d^{-1} using data from CM318 and 20.2 g C m^{-2} d^{-1} using data from CM379 (Table 22); both of these rates are in the anoxic category. The maximum predicted rates were much lower with resuspension on, falling to 0.1 g C m^{-2} d^{-1} (Oxic A) using data from CM318 and to 6.8 g C m^{-2} d^{-1} (Hypoxic B) using data from CM379 (Table 22)

Sediment sulfide data were collected from triplicate samples at 33 locations within the cage array and extending to about 120 m from the cage array on 12 September 2006 (see Chang et al. 2011 for details). The sediment data indicated one small patch of anoxic sediments under the cage at the northwestern corner of the site, totalling 700 m^2, and a total of 4,800 m^2 with Hypoxic B or higher sediments under the cages along the northern and western perimeter of the cage array (Table 23, Fig. 15). The maximum observed sediment sulfide concentration (from means of triplicate subsamples) was in the anoxic category (Table 22).

SITE D

Site D (Fig. 16) had ten 100 m circumference cages, in two rows of five cages each, at the time of sediment sampling (July 2007). The average distance between CHS depth soundings within the DEPOMOD domain was 32 m (range: 3–62 m). Water depths under the cage array ranged from 12–23 m (below Chart Datum), with the shallowest area at the northwest and the deepest at the southern end. The site had a low exposure index (Table 5). The farm was stocked in the spring of 2005 (Table 6). Sediment sampling was conducted on 24 July 2007. Harvesting had started in late June 2007, and at the time of sediment sampling, most of the farm had been harvested (Table 7); one cage had been completely harvested and the other cages were being harvested. The average daily feed rate per cage during 24 June–24 July 2007 ranged from 0–939 kg d^{-1} (Table 8). The overall feed rate during this time was about one-third less than the maximum monthly feed rate, in June 2007 (Fig. 17).

Neither of the current meter deployments (Fig. 16) were concurrent with the July 2007 sediment sampling; however, CM383 did include July data from 2009, while CM409 was in the fall of 2009 (Table 24). Current speeds at site D were low for CM 383, with median speeds ranging from 4.4–5.7 cm s^{-1}, and maximum speeds ranging from 19.1–34.8 cm s^{-1}, and moderate for CM409, with median speeds ranging from 7.8–9.5 cm s^{-1}, and maximum speeds ranging from 34.9–47.7 cm s^{-1} (Table 25); current direction was mainly to the northeast and southwest for both deployments, roughly parallel to the shoreline (Fig. 18). For deployment CM383, currents were stronger to the southwest near the surface, stronger to the northeast near the bottom, and similar in both directions at mid-depth; the highest maximum current speeds in this deployment were near the surface. For deployment CM409, current speeds and directions were similar among depths. The percentage of near-bottom current speeds above the DEPOMOD threshold for resuspension (9.5 cm s^{-1}) showed a large difference between the two current meter deployments: 11% for CM383 and 50% for CM409.

Using the average sinking rates used in DEPOMOD (11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces), the time required for particles to sink from the mean sea level to the seafloor (18.4 m) was 2.8 min for feed pellets and 9.6 min for feces. Simple model predictions using current speed data from CM409 (which had higher mid-depth current speeds) indicated that the area of impact would be considerably larger than that predicted using current speed data from CM383 (Table 26, Fig. 19).

When DEPOMOD was run at site D with resuspension off and average daily feed rates per cage during 24 June to 24 July 2007, all of the waste material remained within the model domain (Table 27). The seafloor area with predicted elevated carbon deposition rates was mostly under the cages, with the intensity related to feed rates; the area with carbon deposition >5 g C m^{-2} d^{-1} was slightly higher using CM383 data (12,700 m^2) than with CM409 data (10,800 m^2), while the area with anoxic rates (>10 g C m^{-2} d^{-1}) was 5,400 m^2 using CM383 data and 3,300 m^2 using CM409 data (Table 28, Fig. 20). With resuspension on, most of the waste material remained within the model domain when using CM383 data, while most of the waste material was transported out of the model domain when using CM409 data (Table 27). With resuspension on, the seafloor area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} when using CM383 data was only 15% smaller than with resuspension off, and still included 4,600 m^2 with anoxic rates; when using CM409 data the seafloor area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} was reduced by 94%, to only 600 m^2, with no area with anoxic rates (Table 28, Fig. 20).

The maximum predicted deposition rates with resuspension off were higher using CM383, than with CM409, and both were in the anoxic category (Table 29). With resuspension on, there was just a slight decrease in the maximum predicted deposition rate using CM383 data, while there was a much larger decrease using CM409 data (Table 29).

Sediment sulfide data were collected from triplicate samples at 41 locations within the cage array and extending to about 130 m from the cage array on 24 July 2007 (see Chang et al. 2011 for details). The sediment data indicated some patches with Hypoxic B or higher sediments under some cages, totalling 3,700 m^2, but no anoxic sediments (Table 30, Fig. 21). The maximum observed sediment sulfide concentration (from means of triplicate subsamples) was in the Hypoxic C category (Table 29).

SITE G

Site G (Fig. 22) had fifteen 70 m circumference cages, arranged in three rows of five cages each, at the time of Tier 2 sediment monitoring (September 2010). The average distance between CHS depth soundings within the DEPOMOD domain was 98 m (range: 21–127 m). Water depths were even under the cage array, averaging 15.0 m below Chart Datum. The site had a moderate exposure index (Table 5). The farm was stocked in May 2009 (Table 6). Harvesting had begun when Tier 2 sediment monitoring was conducted on 8 September 2010 (Table 7): one cage was partially harvested in June 2010, another cage was harvested in September 2010, two more in December 2010, and the remainder during May–July 2011. At the end of August 2010, one cage had been largely harvested, with a remaining biomass of 12 t, while at the other cages, the biomass ranged from 35–47 t. The average daily feed rate during 8 August–11 September 2010 was low in all cages (due to heavy sea louse infestations and the need for starvation prior to anti-louse treatments), ranging from 7.5–27.5 kg d^{-1} (Table 8). The overall feed rate during this time was only about 10% of the maximum feed rate earlier in the summer (Fig. 23). In July 2010, the average daily feed rate per cage ranged from 94 kg d^{-1} in one cage which had been mostly harvested, to 198–284 kg d^{-1} in the other 14 cages (Table 8).

Neither of the current meter deployments (Fig. 22) were concurrent with the Tier 2 sediment monitoring in September 2010. Both were in the summer of 2001 (Table 31), at a time when the cages were not in the same location as in 2010. Current speeds at site G were very low, and nearly identical in the two deployments, with median speeds of 2.5–2.6 cm s^{-1}, and maximum speeds of 9.8–9.9 cm s^{-1} (Table 32), predominantly to the north-northwest and south-southeast, roughly parallel to the shoreline (Fig. 24). The percentage of current speeds above the DEPOMOD threshold for resuspension (9.5 cm s^{-1}) was <1% in both datasets.

Using the average sinking rates used in DEPOMOD (11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces), the time required for particles to sink from the mean sea level to the seafloor (18.9 m) was 2.9 min for feed pellets and 9.8 min for feces. Simple model predictions indicated quite small areas of impacts, with very similar results for the two current speed datasets (Table 33, Fig. 25).

When DEPOMOD was run at site G with resuspension off and average daily feed rates per cage during the month prior to sediment sampling (8 August–11 September 2010), all of the waste material remained within the model domain (Table 34). The model predicted very low impacts (using both sets of current velocity data), with no seafloor area with predicted carbon deposition rates >5 g C m^{-2} d^{-1}, with resuspension off and on (Table 35, Fig. 26).

When DEPOMOD was run at site G with resuspension off and average daily feed rates per cage during July 2010 (when feed rates were high), all of the waste material still remained within the model domain (Table 34), but the model predicted much higher impacts, with carbon deposition rates >5 g C m^{-2} d^{-1} occurring under most of the cage array area (14,000–14,200 m^2) and an area of 1,400 m^2 with anoxic rates (Table 36, Fig. 27). With resuspension on, almost all of the waste material remained within the model domain (Table 34), and there was very little change in the area with predicted carbon deposition rates >5 g C m^{-2} d^{-1} (Table 36, Fig. 27).

The maximum predicted carbon deposition rates, using average daily feed rates during 8 August–11 September 2010 (at the time of sediment sampling) and resuspension off, were low (1.4 g C m^{-2} d^{-1}, in the Oxic B category) using both sets of current meter data, and there was very little change with resuspension on (Table 37). The maximum predicted carbon deposition rates, using the average daily feed rates during July 2010 and resuspension off, were much higher (14.7–15.2 g C m^{-2} d^{-1}, in the Anoxic category), and there was very little change with resuspension on (Table 37).

Sediment sulfide data were collected as part of EMP Tier 2 monitoring conducted by Silk Stevens Ltd. within the cage array at this site (triplicate samples from 46 locations on 8 September 2010). The presence of feed pellets and feces in the sediment samples was reported as being low (0-2%). The Tier 2 sediment data indicated large areas with Hypoxic B or higher (17,500 m^2) and anoxic (3,500 m^2) sediments (Table 38, Fig. 28). Because the sampling did not extend beyond the cage array, and elevated sulfide concentrations were found at the edge of the sampling area, the spatial extent of the area of elevated sulfide concentrations may be underestimated. The maximum observed sediment sulfide concentration (from means of triplicate subsamples) was in the Anoxic category (Table 37).

SITE H

Site H (Fig. 29) had thirty-three 70 m circumference cages, arranged in three rows of 11 cages each, at the time of Tier 2 sediment monitoring (September 2009). This was an IMTA site, with three mussel raft cages (at the eastern end of each cage row) and two kelp rafts (just west of the cage array). The average distance between CHS depth soundings within the DEPOMOD domain was 40 m (range: 2–68 m). Water depths under the cage array ranged from 11–23 m, with the shallowest area to the northwest and the deepest area to the southeast. The site had a low exposure index (Table 5). The farm was stocked in November 2007 (Table 6). EMP Tier 2 sediment monitoring was conducted on 11 September 2009, about two months prior to the date of maximum fish biomass and the start of harvesting (Table 7). At the time of sediment sampling (11 September 2009), the fish biomass per cage was relatively even, varying from 44,300–63,700 kg. The average daily feed rate during the four week period leading up to the sediment sampling date (16 August–12 September 2009) was also relatively similar among cages, ranging from 373–506 kg d^{-1} (Table 8). Sediment sampling was conducted near the time of maximum feeding (Fig. 30).

The two current meter deployments (Fig. 29) were both in the summer of 2009, about one month prior to the September 2009 Tier 2 sediment monitoring (Table 39). For CM381 (located to the northeast of the site), current velocities were relatively similar between the depth layers: current speeds were moderate, with median speeds ranging from 6.5–8.2 cm s^{-1}, and maximum speeds ranging from 24.7–31.4 cm s^{-1}, and the current direction was predominantly to the north and northeast (Table 40, Fig. 31). For CM389 (located to the southwest of the site), current speeds were lower, with median speeds ranging from 5.4–7.1 cm s^{-1} and maximum speeds ranging from 19.1–21.1 cm s^{-1}, with differences in direction between depth layers. Near the surface, currents were predominantly to the south and west; at mid-depth, the currents were mainly to the northeast and west-southwest; while near bottom, currents were mainly to the north-northeast and southwest (Table 40, Fig. 31). The percentage of near-bottom current speeds above the DEPOMOD threshold for resuspension (9.5 cm s^{-1}) showed a large difference between the two current meter deployments: 43% for CM381 and 22% for CM389.

Using the average sinking rates used in DEPOMOD (11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces), the time required for particles to sink from the mean sea level to the seafloor (26.0 m) was 3.9 min for feed pellets and 13.5 min for feces. Simple model predictions of the area of impact were much larger using mid-depth current speeds from CM381 than when using current speeds from CM389 (Table 41, Fig. 32).

When DEPOMOD was run at site H with resuspension off and average daily feed rates per cage during 16 August–12 September 2009, all of the waste material remained within the model domain (Table 42), and the model predicted elevated carbon deposition rates under the entire cage array area, with similar results for the two current velocity datasets: the area with carbon deposition rates >5 g C m^{-2} d^{-1} was 48,800–49,600 m^2 and the area with anoxic rates (>10 g C m^{-2} d^{-1}) was 32,400–33,300 m^2 (Table 43, Fig. 33). With the CM381 data, there was a shift in the area of elevated deposition rates a few meters to the north and northeast, reflecting the predominant current direction, while with the CM389 data (with lower current speeds), the area of elevated deposition rates remained centred under the cage array. With resuspension on, most of the waste material was transported outside the model domain using data from CM381, while the majority of waste material remained within the model domain using data from CM389 (Table 42). The areas with predicted carbon deposition rates >5 g C m^{-2} d^{-1} when using data from CM381 were just 10% of that estimated with resuspension off; when using data from CM389 the area of predicted carbon deposition rates >5 g C m^{-2} d^{-1} showed a much smaller decrease relative to that estimated with resuspension off (Table 43, Fig. 33).

The maximum predicted carbon deposition rates, with resuspension off, were in the Anoxic category (Table 44). With resuspension on, the maximum predicted deposition rate fell by 50% with current velocities from CM381 and by about 8% with CM389, but in both cases were still within the Anoxic category (Table 44).

Sediment sulfide data were collected as part of EMP Tier 2 monitoring conducted by Dominator Marine Services Inc. within the cage array at this site (triplicate samples from 88 locations on 11-15 September 2009). The monitoring report indicated the presence of significant amounts of waste feed, feces, and bacterial mats at the sample locations. The Tier 2 sediment data indicated large areas with Hypoxic B or higher (53,500 m^2) and Anoxic (14,700 m^2) sediments (Table 45, Fig. 34). Because the sampling did not extend beyond the cage array, and elevated sulfide concentrations were found at the edge of the sampling area, the spatial extent of the area of elevated sulfide concentrations may be underestimated. The maximum observed sediment sulfide concentration (from means of triplicate subsamples) was in the Anoxic category (Table 44).

EFFECTS OF CURRENT SPEED AND FEED RATE ON DEPOMOD PREDICTIONS

Among sites, there was no clear relationship between the area of seafloor with DEPOMOD predicted deposition rates >5 g C m^{-2} d^{-1} (resuspension off) and the current speed (Fig. 35). Within each site, higher current speeds usually resulted in smaller areas with elevated deposition rates (except at site A in May 2006), but at all sites the differences in area were small. There was no clear trend (among or within sites) between the maximum predicted deposition rate (resuspension off) and the current speed (Fig. 35).

There was a clear positive trend among sites between the area of seafloor with predicted deposition rates >5 g C m^{-2} d^{-1} (resuspension off) and the feed rate used in DEPOMOD (Fig. 36). There was little indication of a relationship among sites between the maximum predicted deposition rate (resuspension off) and the feed rate used in DEPOMOD (Fig. 36).

EFFECTS OF CURRENT SPEED AND FEED RATE ON SEDIMENT SULFIDE CONCENTRATION

There was no clear relationship among sites between the area of seafloor with sediment sulfide concentrations >3,000 µM and the current speed (Fig. 37). There also was no clear relationship among sites between the maximum sulfide concentration and the current speed (Fig. 37).

There was no clear relationship among sites between the area of seafloor with sediment sulfide concentrations >3,000 µM and the feed rate (Fig. 38). There also was no clear relationship among sites between the maximum sulfide concentration and the feed rate (Fig. 38).

COMPARISON OF RESULTS FROM THE SIMPLE MODEL, DEPOMOD, AND SEDIMENT SAMPLES

Comparisons between the estimated areas of impacted seafloor from the simple model (estimated area of deposition of feed pellets, using median current speed), DEPOMOD (predicted area with carbon deposition rate >5 g C m^{-2} d^{-1}, resuspension off), and sediment samples (>3,000 µM sediment sulfide concentration, equivalent to Hypoxic B or higher) are shown in Table 46 and Figures 39-44.

At Site A in September 2005, the simple model and DEPOMOD produced similar estimates of the spatial extent of impacted seafloor, and both were similar in size to the observed spatial extent of impacted seafloor in the sediment sulfide samples. Neither model predicted the observed spatial heterogeneity very well. At site A in May 2006, the spatial extents of impacted seafloor predicted by the two models were similar, but were about double the observed spatial extent of impacted seafloor in the sediment samples; in addition, the exact locations with elevated impacts were not the same in DEPOMOD and the sediment samples.

At site C, the two models predicted similar estimates of the spatial extent of impacted seafloor, but both models considerably overestimated the spatial extent of impacted seafloor when compared to the observed sediment conditions. DEPOMOD and the simple model predicted impacts under the entire cage array, while the sediment samples indicated impacts under a much smaller area. At site D, the spatial extent of impacted seafloor predicted by the simple model was greater than the DEPOMOD prediction, and both were much larger than the spatial extent of impacted seafloor observed in the sediment samples. At site G, the spatial extent of impacted seafloor predicted by the simple model was somewhat smaller than the observed spatial extent of impacted seafloor, while DEPOMOD, using the feed rate at the time of sediment sampling, predicted no areas of elevated carbon deposition (feed rates were low at this time). However, when higher feed rates from earlier in the summer (July 2010) were used for site G, the DEPOMOD predicted areas of impact that were similar in size to the observed areas of impact. At site H, the spatial extent of impacted seafloor in the two models and in the sediment samples were quite close; all indicated elevated impacts under most of the cage array.

Overall, the spatial extent of areas with elevated impacts predicted by DEPOMOD and the simple model (using median current speeds and feed pellet sinking rates) were quite similar (with the exception of DEPOMOD predictions at site G using feed rates during August-September 2010), although the simple model generally predicted slightly larger impacted areas than DEPOMOD (Table 46, Fig. 45). There were indications of a positive relationship between DEPOMOD predictions of the total area impacted and the measured impact area (based on sediment sulfide concentration), except at site C and at site G using the feed rate at the time of sediment sampling (Table 46, Fig. 46).

There was no clear relationship among sites between the maximum carbon deposition rate predicted by DEPOMOD and the maximum observed sulfide concentration, with resuspension off and on (Fig. 47).

The linear relationships between the observed sediment sulfide concentrations and the predicted carbon deposition rate in the corresponding DEPOMOD grid cells showed high variability, and with generally low r^2 values ranging from 0.03–0.37 (Table 47). In most cases, the data did not fit well with the two equations used by Hargrave (2010) to describe the relationship between these two parameters (Fig. 48-54). The lack of a relationship between these parameters can also be seen when the data for sampling locations from all five study sites are combined (Fig. 55); however, if site G is excluded, the scatter is somewhat reduced. Further analysis of this data is presented in Appendix A.

When the summer-fall sampling locations are examined separately where the DEPOMOD predicted deposition rate was <5 g C m^{-2} d^{-1} (Oxic A to Hypoxic A) at sites A (September 2005), C, D, and H combined (excluding site G), 85% of these combined data points were classed as Oxic A to Hypoxic A according to the sediment sulfide concentration (<3,000 µM), and 15% had higher sulfide concentrations (Fig. 56). On an individual site basis, at three of the four sites, the sampling locations where the predicted deposition rate was classed as Oxic A to Hypoxic A were mostly in the same categories based on the sulfide concentration (Fig. 56): 82-86% at site A and 100% at sites C and D. However, at site H, only 12-33% of the locations with Oxic A to Hypoxic A deposition rates also had sulfide concentrations in the same categories. At site H, there were very few sampling locations where the predicted deposition rate was <5 g C m^{-2} d^{-1} (19% for CM381 and 7% for CM389) because there was no sampling away from the cage array, so there was not a good representation of low impact sampling locations at this site.

When the summer-fall sampling locations are examined separately where the DEPOMOD predicted deposition rate was >5 g C m^{-2} d^{-1} (Hypoxic B to Anoxic) at sites A (September 2005), C, D, and H combined (excluding site G), 64% of these combined data points were classed as Hypoxic B to Anoxic according to the sediment sulfide concentration (>3,000 µM), while 36% had lower sulfide concentrations (Fig. 57). On an individual site basis, at three of the four sites, less than half of the sampling locations where predicted deposition rates were classed as Hypoxic B to Anoxic were in the same categories based on sulfide concentrations (Fig. 57): 38-47% at site A, 10% at site C, and 30-33% at site D. However, at site H, 79-82% of the sampling locations with deposition rates classed as Hypoxic B to Anoxic had sulfide concentrations in the same categories.

DISCUSSION

DEPOMOD PREDICTIONS

DEPOMOD uses site specific data on bathymetry, cage locations and dimensions, current velocity, and feed rates per cage to predict the rate and spatial distribution of organic carbon deposition on the seafloor in the vicinity of fish farms. Also required are data on the waste particle characteristics: feed pellets (water content, digestibility, feed wastage rate, carbon content, settling velocity) and feces (carbon content and settling velocity). Such data are not generally available on a site specific basis, as in the case of our study. For these parameters, values recommended for running DEPOMOD at British Columbia salmon farms (Stucchi and Chamberlain, unpublished data) were used.

There was a positive relationship between the spatial extent of seafloor area with predicted deposition rates >5 g C m^{-2} d^{-1} (with resuspension off) and the feed rate used in DEPOMOD (Fig. 36). The seafloor areas where the predicted deposition rate was >5 g C m^{-2} d^{-1} were directly under the cage array or within a few meters of the cage area, with the highest rates under the cages receiving the most feed. Water currents did not cause a large horizontal displacement of the areas with elevated deposition rates. This is likely because of the shallow depths at the study sites, which mean that feed pellets would only take approximately 3 min or less to reach the seafloor, while feces would take approximately 10 min or less (on average), so the particles would be subject to horizontal displacement by currents for a only a short time.

Higher current speeds would be expected to result in lower intensities of deposition and smaller extents of seafloor area with elevated impacts, due to greater dispersion of waste particles. However, such trends were not observed among sites, either with the DEPOMOD predictions or the sediment sulfide data. This may have been due to the small number of study sites, as well as other factors, such as differences in feed rates among sites. There were indications that within sites, the DEPOMOD predicted areas of elevated impacts were usually smaller with higher current speeds, but the differences in the areas were small.

Current velocity appeared to have a greater effect on resuspension. Running DEPOMOD with resuspension off resulted in predictions that all of the carbon waste would remain within the DEPOMOD domain at all sites. With resuspension on, at sites with low current speeds, such as with the current velocity data from CM383 at site D, CM389 at site H, and both current meter deployments at site G, more than 60% of the waste remained within the mode domain. In all other cases, most of the carbon waste reaching the seafloor was resuspended and transported outside the model domain; less than 25% of the waste remained within the model domain.

Strain and Hargrave (2005) estimated that the amount of organic matter deposited in the immediate vicinity of the cage area at farms in SWNB was 50 times less than the total organic matter waste production by the farm, suggesting that most of the wastes were being transported away from the cages. This suggests that running DEPOMOD with resuspension off could overestimate the impacts on sediments immediately beneath the farm. However, running DEPOMOD with resuspension on appeared to overestimate that amount of waste material that was resuspended and transported out of the model domain at our study sites. In British Columbia, Chamberlain and Stucchi (2007) also reported that running DEPOMOD with resuspension on resulted in overestimation of the transport of particles away from salmon farms. It may, therefore, be appropriate to modify DEPOMOD to allow a different (higher) erosion threshold in the resuspension module, or to use or develop other models that allow adjustments to the threshold speed for resuspension (see below for further discussion on the resuspension module).

COMPARISONS BETWEEN DEPOMOD PREDICTIONS AND MEASURED IMPACTS

Ideally, DEPOMOD predictions of carbon deposition rates should be compared to actual measurements of carbon deposition rates. However, the measure of organic enrichment used in the New Brunswick monitoring program is sediment sulfide concentration (NBDENV 2006). Hargrave et al. (2008) and Hargrave (2010) provide relationships between these two parameters. However, these relationships are based on limited data. Although both parameters provide indications of organic enrichment, there is no direct chemical relationship between these parameters, so the relationship must be used with caution. Nevertheless, high organic carbon deposition rates are associated with high sediment sulfide concentrations, although the precision of this relationship is uncertain. Another factor contributing to uncertainty in the relationship between these parameters is that there is probably a temporal difference between the time when organic material is deposited on the seafloor and the time when changes in the sediment sulfide concentration are detected, and this time lag may vary among sites and seasons. While recognizing this uncertainty, comparisons were made using these parameters, because resource managers have requested DEPOMOD predictions on proposed sites (i.e. carbon deposition rates), while existing farms are monitored for sediment sulfide concentrations, and sediment sulfide data were available at all our study sites.

Brooks (2007) reported that DEPOMOD predictions at salmon farms in British Columbia compared well with measured sediment physicochemical changes, although the actual parameters measured were not given. In our study, DEPOMOD predictions of the spatial extent of impacted seafloor did not consistently agree with the observed spatial extent of impacted seafloor (Fig. 46). The lack of agreement was most notable at sites C and G. At site C, the DEPOMOD predicted area of impact was much larger than the observed area of impact, while at site G, the DEPOMOD predicted area of impact (using the feed rate at the time of sediment sampling) was much smaller than the observed. In the case of site G, the DEPOMOD predicted area was probably low, because the feed rate was very low around the time of sediment sampling. However, the feed rate at this site had been much higher just a few weeks earlier, and when DEPOMOD was re-run using a higher feed rate from earlier in the summer, the predicted spatial extent of impacted seafloor was close to the observed area of impacted seafloor.

The relationship between sediment sulfide concentrations and feed rates in cages appears to be complex. There was no clear relationship among sites between the area of elevated sulfide concentration (>3,000 µM) and the feed rate at the time of sampling (Fig. 38). There was also no clear relationship among sites between the maximum sulfide concentration and the feed rate (Fig. 38). At some sites, elevated sediment sulfide concentrations were found under cages receiving the highest amounts of feed, but at other sites this was not the case. At site A in September 2005 and at site D, where feed rates varied considerably among cages, the highest sulfide concentration areas were sometimes, but not always, under the cages receiving the highest amounts of feed. However, at site A in May 2006, there was no clear association between the higher sulfide concentration areas and the amounts of feed added per cage. At site H, feed rates were high at all cages at the time of sediment sampling, and sediment sulfide concentrations were high under most of the cage array. However, at site C, feed rates were also relatively even among the cages, but elevated sulfide concentrations (>3,000 µM) were only found under one corner cage. At site G, feed rates were low in all cages during the five weeks leading up to the sediment sampling date; however, sediment sulfide concentrations were high under most cages.

The relationship between sediment sulfide concentrations at individual sampling locations and the DEPOMOD-predicted carbon deposition rates (with resuspension off) in the corresponding grid cell (see Fig. 48-55) showed considerable scatter, and often did not fit the Hargrave (2010) equations. This may be in part due to the small-scale variability in the sulfide data (see Chang et al. 2011). Another problem with the sulfide data was the lack of data from outside the cage array at sites G and H. Our findings suggest that the Hargrave (2010) equations may not be universal. It should be noted that the Hargrave (2010) equations were derived mostly from British Columbia data, and that there was considerable variability in the relationship between these parameters in those data (Chamberlain and Stucchi 2007).

Hargrave (1994) and Cranston (1994) reported that organic sedimentation rates greater than approximately 1 g C m^{-2} d^{-1} can lead to negative impacts at salmon farms. More recent work by Chamberlain and Stucchi (2007) found that high sulfide concentrations occurred at carbon deposition rates above 1–5 g C m^{-2} d^{-1} at British Columbia salmon farms. In our SWNB study, the relationship between sulfide concentration and DEPOMOD predictions of carbon deposition rates was highly variable. Low predicted carbon deposition rates (<5 g C m^{-2} d^{-1}) were usually associated with low sulfide concentrations (<3,000 µM), but high predicted carbon deposition rates (>5 g C m^{-2} d^{-1}) were associated with a wide range of sulfide concentrations. Possible explanations include small-scale variations in sulfide measurements, bathymetry, current velocities, and oxygen fluxes.

At site A, where sediment sulfide data were obtained on two dates, there were indications of seasonal effects. Sediment sulfide concentrations were lower in May 2006 than in September 2005. However, DEPOMOD predicted higher impacts in May 2006, due to higher feed rates than in September 2005. The lower sulfide concentrations in May 2006 may have been due to resuspension of wastes during winter storms. This was the most exposed of our study sites, and the winds in SWNB are highest during the winter (Peterson et al. 2001), the period between the two sampling events at this site. Divers working at fish farms in SWNB have reported that winter storms often resuspend and disperse wastes that have accumulated under fish farms during the previous months. This suggests that the default value for consolidation time (4 days) may not be appropriate, at least in SWNB. It may be more appropriate to use a longer consolidation time that would allow resuspension of wastes that have accumulated over a longer period; however, the appropriate consolidation time is not known. The possibility of seasonal effects, such as winter storms, suggests that it may not be appropriate to compare DEPOMOD predictions among farms using data from different times of the year.

For farms that have begun harvesting, feed rates are often low, but actual sediment sulfide concentrations may reflect earlier, higher feed rates. In a previous study in SWNB (Page et al. 2011), decreases in sulfide concentrations lagged behind decreases in biomass and feed rates due to harvesting or other reasons. This has also been observed at salmon farms in British Columbia (Brooks 2001). In another study (Chang and Page 2011), it was found that sediment sulfide concentrations measured during Tier 1 monitoring usually recovered to oxic levels within a few months after harvesting was completed, but the recovery time could vary widely among farms. In the present study, sediment data were obtained at two farms where feed rates had declined significantly from earlier in the year, sites D and G. At site D, the feed rate near the time of sampling was about a third less than the peak feed rate earlier in the summer, but still resulted in a DEPOMOD estimated area of impacted seafloor that was considerably larger than the observed area of impacted sediments. At site G, the feed rate at the time of sampling was only about 20% of the peak feed rate earlier in the summer, and produced a DEPOMOD prediction of very low impacts, while observed seafloor impacts were high; however, when higher feed rates from earlier in the year were used, the DEPOMOD prediction was similar to the observed sediment conditions at this site. This suggests that sediment conditions at the time of sampling at site G were reflecting higher carbon deposition rates from earlier in the year; despite having low feed rates for about a month prior to sediment sampling, the sediments had not yet recovered. The very low current speeds at site G may have been a factor in the apparently slow recovery time of sediments at this site.

SIMPLE MODEL

With the simple model, higher current speeds resulted in predictions of larger areas of impact. This was because the simple model did not predict the intensity of impact; it only predicted the area of impact, as determined by the estimated displacement of waste particles, and this would be greater with higher current speeds. On the other hand, with DEPOMOD, higher current speeds resulted in smaller areas with the highest impacts (see above).

The simple model (based on estimated displacement of feed pellets at median mid-depth current speed) and DEPOMOD (with resuspension off) produced similar predictions of the spatial extent of impacted seafloor (equivalent to Hypoxic B or higher) in most cases. In the case of site G, DEPOMOD predicted much lower impacts than the simple model when using the feed rate at the time of sediment sampling (the feed rate was low at the time). However, when DEPOMOD was run at this site with a higher feed rate (from July 2010, about two months earlier), the DEPOMOD predicted spatial extent of impacted seafloor was closer to (and actually slightly larger than) the simple model prediction.

DEPOMOD SOURCES OF UNCERTAINTY

There are several possible sources of uncertainty related to DEPOMOD predictions. These include:

- Influence of cage infrastructure on current velocity.
- Use of current velocity data from a single point.
- Spatially-limited bathymetry data.
- Choice of appropriate feed rate.
- Feed pellet and feces characteristics (feed composition, sinking rates).
- Cage movement.
- Temporally constant depth (lack of tidal variation).
- Limitations of the resuspension module: use of fixed resuspension thresholds and the effects of waves and winds.
- Choice of grid interpolation technique for contouring the model output data.

Influence of Cage Infrastructure on Current Velocity

Current velocity data for proposed farms will usually be obtained before any farm infrastructure is onsite. The presence of cages and related infrastructure will have an impact on current velocities, which can affect model predictions.

Use of Current Velocity Data from a Single Point

DEPOMOD uses current velocity data input from one current meter deployment at the study site. Our current meter deployments indicated that there is some spatial and/or temporal variability in currents within the immediate vicinity of some farms, resulting in differences in DEPOMOD predictions using the different current meter datasets. Therefore, the use of current velocity data from just one location will not account for small-scale differences in water currents within the spatial domain of the prediction. However, obtaining multiple current meter records from each operating farm may not always be feasible. The use of a circulation model such as FVCOM (Chen et al. 2006) may capture some of the fine-scale spatial heterogeneity of water currents, thus potentially resulting in improved predictions of carbon sedimentation rates at some sites. Nevertheless, the differences in predicted deposition patterns resulting from using different current meter datasets at our study sites were not great, probably because of the relatively short duration that particles spend in the water column.

There are also seasonal changes in currents. While the current meter deployments used in this study were at least one month in length, they were not long enough to account for seasonal variations. Also, because the current meter deployments in our study were usually not at exactly the same time as the sediment sulfide measurements, the accuracy of the model predictions may have been affected. Water circulation in the SWNB area is dominated by strong tidal forcing – the tidal range can exceed 8 m – but there can also be seasonal variations due to wind and freshwater discharges (Trites and Garrett 1983). However, since the time that particles such as feed pellets spend in the water column is quite short, the influence of the temporal variations in current velocity would not be expected to be large.

Spatially-limited Bathymetry Data

Bathymetry data are generally not available at the spatial scale of DEPOMOD grid cells (i.e. 10-20 m in our study), so interpolation from available data is usually required. In our study sites, the average distance between depth soundings ranged from 23 m at site C to 98 m at site G (mean of distances between each depth sounding and the nearest neighboring sounding). This means that fine-scale depth variations may be missed. As reported in Appendix B, the effects on DEPOMOD predictions of varying the sea level (and hence, total water depth) within a range of a few meters may be relatively small. However, small-scale hollows in the seafloor (which may not be detected by the available bathymetry data) may serve as sinks for organic deposition, and such fine-scale variations would not be reflected in DEPOMOD predictions.

Choice of Appropriate Feed Rate

Feed rates are very important in determining the outcome of DEPOMOD predictions. Therefore, it is important that the appropriate feed rates are used in the model. For predicting impacts of proposed farms, the proposed maximum feeding rates would be appropriate (Cromey et al. 2000). However, for predicting impacts of operating farms, the appropriate feed rate may be difficult to determine, if the intent is to check for agreement with sediment sampling data. This is because there will likely be a lag between the time when waste feed hits the seafloor and the time when the effects on sediment sulfide concentrations are manifest, and the length of this lag may vary between sites and seasonally. For operating farms where fish are growing and feed rates are near the peak for the year (such as in summer-fall), the average feed rates around the time of sediment sampling are probably appropriate. However, if harvesting has begun, resulting in rapidly decreasing feed rates, a feed rate from an earlier period may be more appropriate. Because there can be large daily variations in feeding, average feed rates over a longer period should be used; we used daily feed rates averaged over four to five week periods.

Feed Pellet and Feces Characteristics

Chamberlain and Stucchi (2007) using the DEPOMOD model at British Columbia salmon farms, predicted that with a feed wastage rate of 5%, waste feed accounted for almost half of the carbon reaching the seafloor, and that at higher feed wastage rates, waste feed would be the dominant contributor of carbon reaching the seafloor. They also found that changing the DEPOMOD input values for the percentage of feed wasted resulted in large changes in the estimated carbon deposition rates. The DEPOMOD default value of 3% of feed wasted (recommended by Stucchi and Chamberlain, unpublished data) was used here. This is within the range reported at salmon farms in British Columbia, where Brooks and Mahnken (2003) reported feed wastage of 5% or less for dry feed. Cromey et al. (2002) also reported that sustainable feed wastage rates could be <5% in Scotland. Strain and Hargrave (2005), however, estimated that the feed wastage rate in salmon farms in SWNB in 2002 was 17% based on carbon, and that waste feed dominated the solid waste production. When Chamberlain and Stucchi (2007) increased the feed wastage rate from 5% to 10%, as well as from 10% to 15%, at a British Columbia salmon farm, the DEPOMOD predicted carbon deposition rates almost doubled. An examination of the effects of increasing feed wastage rates at four of our SWNB study sites, indicated that increasing the feed wastage rates from 5% to 10% and from 10% to 15% resulted in increases in the maximum predicted carbon deposition rates by factors of 1.3-1.7, while the spatial extent of seafloor area with elevated carbon deposition rates (>5 g C m^{-2} d^{-1}) increased by smaller factors, ≤1.2 (see Appendix C). In our DEPOMOD predictions using the 3% feed wastage rate, the spatial extent of impacted seafloor was found to be similar to or greater than that observed in the sediment samples in most cases, suggesting that a 3% feed wastage rate may be a reasonable estimate, if not an overestimate of actual rates in SWNB. It has been reported that feed wastage rates for salmon farming worldwide have declined significantly over time (Cromey et al. 2002; Reid et al. 2009), and recent unpublished information suggests that current feed wastage rates for pre-market fish in SWNB could be as low as 1%, although for younger fish (when total biomass and feed rates are much smaller), feed wastage rates are probably higher (M. Szemerda, Cooke Aquaculture, pers. comm.).

Recent information indicates that the some of the characteristics of feeds now in use in SWNB are somewhat different than the values used in our study (recommended values from Stucchi and Chamberlain, unpublished data). Feed digestibility is now reported to be about 75%, the water content of feed is about 5%, and the carbon content of feed is about 52% (M. Szemerda, Cooke Aquaculture, pers. comm.); the corresponding values used in our study were 90%, 10%, and 57%, respectively (see Table 2). An investigation into the effect of using these revised feed characteristics is reported in Appendix D. The net effect was to increase the waste production per unit of feed, resulting in increased areas with elevated seafloor impacts and increased maximum deposition rates.

Uncertainty regarding the sinking rates of feed pellets and feces is another factor that may affect the accuracy of model predictions. As noted above, settling velocities recommended for British Columbia salmon farms (Stucchi and Chamberlain, unpublished data) were used: 11.0 cm s^{-1} for feed pellets and 3.2 ± 1.1 cm s^{-1} (mean ± SD) for feces. Salmon feed pellets are now manufactured to have a sinking rate of 10–11 cm s^{-1} (S.C. Backman, Skretting, St. Andrews, NB, pers. comm.; M.J. Beattie, New Brunswick Department of Agriculture, Aquaculture and Fisheries, St. George, NB, pers. comm.), which agrees with the value used here. Published data on fecal settling rates for salmon are highly variable. A review by Reid et al. (2009) reported that measured settling rates for salmonid feces ranged from 0.7-9.2 cm s^{-1}; the fecal settling rate that was used here was based on laboratory measurements by Cromey et al. (2002).

Cage Movement

Another potential source of error is that DEPOMOD does not include horizontal movement of cages. Although precise data are lacking, it appears that cages in SWNB can move up to 10 m or more horizontally during a tidal cycle. Such movement would effectively spread out the wastes from each cage over a larger area, thus possibly decreasing the intensity of the highest impacts. A preliminary study at a Scottish salmon farm where horizontal cage movement was mostly within 5 m from a starting point found no significant effect of cage movement on predicted deposition rates (Cromey and Black 2005).

Temporally Constant Depth

Another possible source of error when running DEPOMOD for SWNB fish farms is that the model uses a temporally constant water depth, equivalent to the mean tidal elevation. Cromey et al. (2002) noted that DEPOMOD predictions were insensitive to tidal change, especially where the tidal range is small relative to the water depth, as in Scotland, where the tidal variation is generally <10% of the water depth at fish farms. In SWNB, however, the tidal range is often 20-30% of the water depths at fish farms, so not accounting for the tidal changes in water depth may affect the accuracy of predictions. Nevertheless, when DEPOMOD results were compared using sea levels equivalent to average low, mid, and high tidal heights, relatively little effect was found on the predictions (see Appendix B).

Limitations of the Resuspension Module

As noted above, running DEPOMOD with resuspension on appeared to overestimate the transport of waste particles away from farms due to resuspension. Chamberlain and Stucchi (2007) reported similar findings in British Columbia. They attributed this to the use of a single critical erosion threshold current speed of 9.5 cm s^{-1}, citing work by Sutherland et al. (2006) which found that current speeds of about 16 cm s^{-1} or higher were needed to transport feed pellets deposited on the seafloor. Chamberlain and Stucchi (2007) noted that the DEPOMOD resuspension module was originally validated at Scottish sites with relatively low current speeds. Near-bottom current speeds at the two sites studied by Cromey et al. (2002) averaged 3.6–6.2 cm s^{-1}, compared to an average near-bottom speed of 7.9 cm s^{-1} at the British Columbia farm in the Chamberlain and Stucchi (2007) study, and 5.9–12.1 cm s^{-1} at the farms in our study, except site G (which had very low current speeds). In our study, it was only in the cases where near-bottom current speeds were very low, that resuspension did not result in most of the carbon deposition being resuspended and transported away from the model domain: at site D using current velocities from CM383 (average near-bottom speed 5.9 cm s^{-1}, with 11% of data records >9.5 cm s^{-1}); site H using current velocities from CM389 (average near-bottom speed 6.6 cm s^{-1}, with 22% of data records >9.5 cm s^{-1}); and site G using data from both current meter deployments (average speed 2.0 cm s^{-1}, with <1% of data records >9.5 cm s^{-1}). In all other cases, the percentage of near-bottom current velocity records with speeds >9.5 cm s^{-1} ranged from 43-66%, resulting in 90-100% reductions in the predicted areas of impact when resuspension was turned on.

Another factor that can affect resuspension is waves. The effects of waves can be more important in shallow waters, especially in exposed locations. However, data on waves are more difficult to obtain and were not available at our study sites. When running DEPOMOD with resuspension on, there is an option to enter wind speed and direction and fetch data, but this module has apparently not been validated for fish farms (Cromey et al. 2002), and our study did not attempt to use it. Cromey et al. (2002) indicated that DEPOMOD has limited scope in shallow sites (<15 m water depth below cages) where the cages may be subject to a large degree of wind-wave resuspension. Our SWNB study sites were in shallow waters, but most were in relatively protected locations; only site A had a high exposure index. However, in Nova Scotia, many fish farms are located in shallow, exposed sites where wind-wave resuspension may dominate. At such sites, DEPOMOD must be used with caution.

Choice of Grid Interpolation Technique for Contouring the Model Output Data

The grid interpolation technique used to contour the model output data affects the contour areas for each carbon deposition rate category. The grid interpolation technique used in this study (rectangular) was based on recommendations in the contouring software (MapInfo Corporation 2005) for data distributed in an evenly spaced pattern, such as DEPOMOD outputs. An investigation into the effects of using other grid interpolation techniques is included in Appendix E. The different grid interpolation techniques had very little impact on the contour plots.

CONCLUSIONS

Predictions of the spatial extent of elevated impacts using DEPOMOD and a simple model showed relatively good agreement. However, the model predictions did not consistently agree with measurements of the spatial extent of impacted sediments based on sulfide concentrations. DEPOMOD predictions of the intensity of impacts also did not consistently agree with actual measurements of the intensity of sulfide concentrations in seafloor sediments.

Despite the poor relationship between predicted deposition rates and sediment sulfide concentration, the results suggest that DEPOMOD can provide some useful information for resource managers. Specifically, when DEPOMOD predicts low deposition rates, it is likely that sediment sulfide concentrations will also be low. Exceptions to this would be cases such as site G, where feed rates were low at the time of sediment sampling but had recently been much higher. In such cases, running DEPOMOD with the earlier, higher feed rates may be appropriate. The most common scenario for using DEPOMOD will likely be in predicting impacts at proposed farms. In such cases, if the model results using proposed maximum feed rates predict low impacts, this suggests that there is a low risk of significant impacts due to organic carbon deposition on the seafloor.

On the other hand, when DEPOMOD predicts high impacts, there is some risk that poor sediment conditions may occur, but there is high likelihood that actual sediment conditions may not be poor. For the resource manager, the DEPOMOD results would suggest a “conservative” scenario, i.e. it is unlikely that actual conditions would be worse than the DEPOMOD predictions. However, from the fish farmer’s viewpoint, it could mean rejecting a site where there is a strong possibility that seafloor impacts might not occur. In such cases, other inputs must be considered in the decision-making process.

Our study suggests that in SWNB, factors other than feed rates (per cage) and current velocities (using data from a single current meter deployment) are also important in determining where the most highly impacted sediments will occur. Fine-scale heterogeneity in bathymetry and water circulation, waves (especially in shallow water or exposed sites), large resuspension events such as storms, and fish husbandry practices, especially those related to feeding, may be important factors in determining the actual distribution of organic deposition under fish farms. In other salmon farming areas, such as Nova Scotia, non-tidal water currents and waves are likely to have a greater impact than in SWNB, where tidal currents predominate.

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Table 1. Environmental Management Program (EMP) site ratings based on sediment sulfide concentration (NBDENV 2006) and corresponding carbon deposition rate as predicted by DEPOMOD (Chamberlain and Stucchi 2007; Hargrave et al. 2008; Hargrave 2010).

EMP rating	Impact on marine sediments under farm (from EMP)	Biodiversity of macrobenthic infauna	Sediment sulfide concentration (μM)	Carbon deposition rate (DEPOMOD) (g C m^{-2} d^{-1})
Oxic A	Low	High	<750	<1.0
Oxic B	Low	Moderate	750–1,500	1.0–2.0
Hypoxic A	May be causing adverse effects	Reduced	1,500–3,000	2.0–5.0
Hypoxic B	Likely causing adverse effects	Reduced	3,000–4,500	5.0–7.5
Hypoxic C	Causing adverse conditions	Reduced	4,500–6,000	7.5–10.0
Anoxic	Causing severe damage	Very low	>6,000	>10.0

Table 2. DEPOMOD input values.

Parameter	Value
Grid generation module (values set by user)	
Grid cell dimensions (major and minor grids)	10 × 10 m (except 20 × 20 m at site H)
Number of major grid cells	99 × 99
Number of minor grid cells	98 × 98
Particle tracking module	
Material type	carbon
Release type	continuous release of food
Particle information (from Stucchi and Chamberlain, unpublished data)	
Food water content	10%
Food digestibility	90%
Food wasted as % of food fed (default value)	3%
Carbon as % of feed pellets (dry weight)	57%
Carbon as % of feces (dry weight)	33%
Settling velocity of feed pellets	11.0 cm s^{-1}
Settling velocity of feces	3.2 ± 1.1 cm s^{-1}
Current velocity data (see Cromey et al. 2002)	
Current velocity layers	3: near-surface, mid-depth, near-bottom (except 1 layer only at site G)
Current velocity time step (default value)	3,600 s (1 h)
Turbulence model (default values)	
Random walk model	Yes
Dispersion coefficient x	0.100 m^2 s^{-1}
Dispersion coefficient y	0.100 m^2 s^{-1}
Dispersion coefficient z	0.001 m^2 s^{-1}
Particle trajectory model (default values)	
Number of particles (for each particle type, per cage, at every time step)	10
Trajectory evaluation accuracy (model time step)	High (60 s)
Resuspension module	
Number of loops to run model for (Cromey et al. 2000)	2
Consolidation time of particles (default value)	4 d
Critical erosion threshold (non-adjustable)	9.5 cm s^{-1}

Table 3. Baseline (at site A) or reference site (all other sites) sediment sulfide concentrations at or near study sites.

Site	First year of operations	Baseline or reference sediment sulfide concentrations			
		Date	Sulfide (μM)	Location	Data source
A	2001	Feb 2001	46–265	On site	Dominator Marine Services
C	1989	Jul 1994	130–140	1.4 km to NE	Hargrave et al. (1995)
D	1989	Sep 1994	100–170	0.3 km to N	Hargrave et al. (1995)
G	1996	Sep 1994	31–53	5.5 km to ENE	Hargrave et al. (1995)
H	1987	Sep 1994	100–170	1.3 km to ENE	Hargrave et al. (1995)

Table 4. Water column depths at study sites. The seafloor depth below chart datum (CD, lowest normal tide) at each site is the average of Canadian Hydrographic Service (CHS) soundings taken under the cage array. Tidal data are from the nearest CHS reference or secondary port. The tide range is the difference between high and low tide.

Site	Seafloor depth under cage array (m below CD)	Mean sea level (m above CD)	Mean water column depth (m from sea level to seafloor)	Mean tide range (m)	Large tide range (m)
A	16.2	4.0	20.2	6.0	8.0
C	19.5	3.9	23.4	5.5	7.8
D	14.6	3.8	18.4	5.5	7.8
G	15.0	3.9	18.9	6.0	8.0
H	22.2	3.8	26.0	5.5	7.8

Table 5. Exposure index values for each of the study sites. The exposure index was developed by Peterson et al. (2001), based on monthly wind velocity data from the Saint John airport over one year (using 1995 data) and the distance of open water from each site to the nearest land in 16 compass directions. A higher index value is an indication of higher exposure.

Site	Exposure index
A	20.6
C	10.1
D	8.5
G	11.1
H	6.6

Table 6. Cage sizes and salmon stocking data at study sites. All cages had circular, plastic collars.

	Cage sizes			Salmon stocking		
Site	n	Circumference (m)	Diameter (m)	Dates	Mean number per cage	Total number
A	13	100	32	Sep-Nov 04	36,480	479,600
	1	50	16	Oct 04	5,370	
C	15	100	32	May-Jun 05	29,850	447,700
D	10	100	32	Spring 05	~30,000	~300,000
G	15	70	22	May 09	13,570	203,600
H	33	70	22	Nov 07	15,050	496,500

Table 7. Farmed salmon numbers and biomass at stocking, at the time of sediment sampling, and maximum levels at study sites. n/a = data not available.

	Stocking			At sediment sampling			Maximum biomass		
Site	Dates	n	Biomass (t)	Date	n	Biomass (t)	Date	Biomass (t)	Harvest Period
A	Sep-Nov 04	484,300	53	22 Sep 05 24 May 06	461,600 453,000	480 1,400	Jul 06	1,880	Aug 06–Aug 07
C	May-Jun 05	447,700	50	12 Sep 06	408,500	1,720	Oct 06	2,100	Nov 06–Mar 07
D	Spring 05	~300,000	n/a	24 Jul 07	55,400	280	Jul 07	1,170	Jun–Jul 07
G	May 09	203,600	15	8 Sep 10	143,000	510	Jul 10	610	Jun 10–Jul 11
H	Nov 07	496,500	56	11 Sep 09	439,400	1,770	Nov 09	2,200	Nov 09–Feb 10

Table 8. Feed rates on or near the dates of sediment sampling at salmon farm sites. For site G, which had low feed rates at the time of sediment sampling due to harvesting, higher feed rates from July 2010 are also shown.

	Cages			Average daily feed rates (kg d^{-1} per cage)				
Site	Circumference (m)	n	Sediment sampling date	Time period	Min.	Max.	Mean	Total feed added to sampling date (kg)
A	100 50	13 1	22 Sep 05	Sep 05	363 203	1,045 203	495 203	681,800
A	100 50	13 1	24 May 06	May 06	615 180	1,113 180	749 180	2 184,600
C	100	15	12 Sep 06	Sep 06	850	1,012	948	2 230,900
D	100	10	24 Jul 07	24 Jun–24 Jul 07	0	939	493	1 930,900
G	70	15	8 Sep 10	8 Aug–11 Sep 10 Jul 10	8 94	28 284	19 235	848,500
H	70	33	11-15 Sep 09	16 Aug-12 Sep 09	373	506	439	3 069,700

Table 9. Dates, durations, and depth layers for current meter (CM) deployments at site A. Current velocities were measured using Acoustic Doppler Current Profilers deployed about one meter above the seafloor. The average depth from the water surface to the seafloor was estimated from CHS bathymetry and tidal data.

CM	Start date	End date	Duration (d)	Average depth from surface to seafloor (m)	Depth layer	
324	12 Jan 05	19 Apr 05	97	20.5	Near surface:	3.5 m below surface
					Mid-depth:	9.7 m above seafloor
					Near bottom:	4.7 m above seafloor
329	13 Sep 05	24 Oct 05	41	20.4	Near surface:	3.5 m below surface
					Mid-depth:	9.7 m above seafloor
					Near bottom:	4.7 m above seafloor
330	13 Sep 05	24 Oct 05	41	18.2	Near surface:	3.5 m below surface
					Mid-depth:	8.7 m above seafloor
					Near bottom:	4.7 m above seafloor

Table 10. Summary of water current speed data collected during three current meter deployments at site A.

Current meter deployment:	CM324	CM329	CM330
Near surface current speeds (cm s^{-1})			
Minimum	0.1	0.1	0.1
Median (50th percentile)	7.0	7.7	9.1
Mean	8.1	9.7	10.8
75th percentile	10.7	13.1	15.0
Maximum	44.3	35.6	41.4
Mid-depth current speeds (cm s^{-1})			
Minimum	0.1	0.1	0.1
Median (50th percentile)	7.7	8.8	9.4
Mean	9.0	10.6	11.1
75th percentile	12.2	14.9	15.3
Maximum	37.7	37.9	38.3
Near-bottom current speeds (cm s^{-1})			
Minimum	0.1	0.4	0.6
Median (50th percentile)	9.1	9.6	9.4
Mean	10.8	10.9	10.9
75th percentile	15.0	14.5	14.7
Maximum	41.1	41.0	36.4
% of near-bottom records >9.5 cm s^{-1}	47	50	49

Table 11. Estimated areas of impacted seafloor at site A using a simple model and mid-depth current speed data from three current meter deployments (CM324, CM329, and CM330) near the site.

Particle type	Mid-depth current speed	Impacted seafloor area (m^2)		
		CM324	CM329	CM330
Feed pellets	Median	33,300	35,700	36,800
	Maximum	92,300	92,800	93,600
Feces	Median	68,500	76,200	80,600
	Maximum	385,300	388,000	393,700

Table 12. DEPOMOD mass balance calculations at site A. The rate of waste released from the farm was calculated from the feeding rate and the estimated rate of waste production per unit of feed, based on the feed and feces characteristics. The percent of waste deposition within the model domain (1 × 1 km) was calculated from the predicted waste deposition rates within each model grid cell.

Sediment sampling date	CM	Total feed rate (kg d^{-1})	Waste produced per kg feed (kg)	Waste produced (kg C d^{-1})	% of waste within the DEPOMOD domain	
					Resuspension off	Resuspension on
Sep 05	324	6,644	0.044	292	100	<1
	329	6,644	0.044	292	100	2
	330	6,644	0.044	292	100	4
May 06	324	9,919	0.044	436	100	1
	329	9,919	0.044	436	100	3
	330	9,919	0.044	436	100	6

Table 13. Estimated areas of seafloor within Environmental Management Program (EMP)classifications at site A, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during September 2005 and current velocity data from three current meter deployments (CM324, CM329, and CM330) at locations near the site (see Fig. 1). The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Contour area (m^2)		Change due to resuspension	
		Resuspension off	Resuspension on	Area (m^2)	% change
CM324					
Oxic A	0.3-1.0	21,600	500	-21,000	-98
Oxic B	1.0-2.0	10,500	200	-10,300	-98
Hypoxic A	2.0-5.0	12,300	0	-12,300	-100
Hypoxic B	5.0-7.5	13,800	0	-13,800	-100
Hypoxic C	7.5-10.0	8,900	0	-8,900	-100
Anoxic	>10.0	4,000	0	-4,000	-100
>5 g C m^{-2} d^{-1}	>5.0	26,700	0	-26,700	-100
CM329					
Oxic A	0.3-1.0	30,400	3,000	-27,300	-90
Oxic B	1.0-2.0	13,800	500	-13,300	-96
Hypoxic A	2.0-5.0	15,400	200	-15,200	-99
Hypoxic B	5.0-7.5	16,200	0	-16,200	-100
Hypoxic C	7.5-10.0	6,800	0	-6,800	-100
Anoxic	>10.0	2,800	0	-2,800	-100
>5 g C m^{-2} d^{-1}	>5.0	25,800	0	-25,800	-100
CM330					
Oxic A	0.3-1.0	38,700	10,700	-28,100	-72
Oxic B	1.0-2.0	18,500	1,700	-16,800	-91
Hypoxic A	2.0-5.0	22,200	300	-21,800	-99
Hypoxic B	5.0-7.5	14,900	0	-14,900	-100
Hypoxic C	7.5-10.0	4,100	0	-4,100	-100
Anoxic	>10.0	2,400	0	-2,400	-100
>5 g C m^{-2} d^{-1}	>5.0	21,400	0	-21,400	-100

Table 14. Estimated areas of seafloor within EMP classifications at site A, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during May 2006 and current velocity data from three current meter deployments (CM324, CM329, and CM330) at locations near the site (see Fig. 1). The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Contour area (m^2)		Change due to resuspension	
		Resuspension off	Resuspension on	Area (m^2)	% change
CM324					
Oxic A	0.3-1.0	23,800	1,600	-22,200	-93
Oxic B	1.0-2.0	11,100	300	-10,800	-97
Hypoxic A	2.0-5.0	12,900	100	-12,800	-99
Hypoxic B	5.0-7.5	5,500	0	-5,500	-100
Hypoxic C	7.5-10.0	8,100	0	-8,100	-100
Anoxic	>10.0	18,700	0	-18,700	-100
>5 g C m^{-2} d^{-1}	>5.0	32,300	0	-32,300	-100
CM329					
Oxic A	0.3-1.0	32,000	13,900	-18,100	-57
Oxic B	1.0-2.0	16,100	2,800	-13,300	-83
Hypoxic A	2.0-5.0	16,000	400	-15,600	-98
Hypoxic B	5.0-7.5	7,000	0	-7,000	-100
Hypoxic C	7.5-10.0	10,000	0	-10,000	-100
Anoxic	>10.0	15,900	0	-15,900	-100
>5 g C m^{-2} d^{-1}	>5.0	32,900	0	-32,900	-100
CM330					
Oxic A	0.3-1.0	38,100	16,800	-21,300	-56
Oxic B	1.0-2.0	22,100	8,300	-13,800	-62
Hypoxic A	2.0-5.0	20,800	800	-19,900	-96
Hypoxic B	5.0-7.5	9,900	0	-9,900	-100
Hypoxic C	7.5-10.0	11,000	0	-11,000	-100
Anoxic	>10.0	11,800	0	-11,800	-100
>5 g C m^{-2} d^{-1}	>5.0	32,700	0	-32,700	-100

Table 15. Maximum predicted carbon deposition rates and maximum observed sediment sulfide concentrations at site A. The maximum deposition rate is the highest of all predicted carbon deposition rates within the DEPOMOD domain. The maximum sediment sulfide concentration is the highest of the sample location means (from triplicate subsamples). DEPOMOD was run using feed rates in September 2005 and May 2006, corresponding to two sediment sulfide sampling events.

Feed rate and sediment sampling month	CM	Maximum predicted deposition rate (g C m^{-2} d^{-1})		Maximum sediment sulfide concentration (µM)
		Resuspension off	Resuspension on	
Sep 05	324	25.5	1.9	
	329	24.2	4.1	10,250
	330	20.4	3.3	
May 06	324	27.7	3.1	
	329	26.9	4.9	5,170
	330	22.5	3.8	

Table 16. Areas of seafloor within EMP classifications at site A, based on the sulfide concentration in sediment samples collected on 22 September 2005 and 24 May 2006 (Chang et al. 2011). The Oxic A category excludes areas where the sulfide concentration was below the estimated background concentration of 300 µM.

Site Classification	Sediment sulfide concentration (µM)	Seafloor area (m^2)	
		Sep 2005	May 2006
Oxic A	300 – 750	68,000	28,300
Oxic B	750 – 1,500	31,600	39,800
Hypoxic A	1,500 – 3,000	42 200	36,900
Hypoxic B	3,000 – 4,500	13,700	15 200
Hypoxic C	4,500 – 6,000	10,500	1,800
Anoxic	>6,000	8,000	0
≥Hypoxic B	>3,000	32,200	17,000

Table 17. Dates, durations, and depth layers for current meter deployments at site C. Current velocities were measured using Acoustic Doppler Current Profilers deployed about one meter above the seafloor. The average depth from the water surface to the seafloor was estimated from CHS bathymetry and tidal data.

CM	Start date	End date	Duration (d)	Average depth from surface to seafloor (m)	Depth layer	
318	21 Aug 03	7 Oct 03	48	24.8	Near surface:	3.5 m below surface
					Mid-depth:	14.5 m above seafloor
					Near bottom:	4.5 m above seafloor
379	7 Jun 09	25 Aug 09	80	21.8	Near surface:	3.5 m below surface
					Mid-depth:	10.7 m above seafloor
					Near bottom:	4.7 m above seafloor

Table 18. Summary of water current speed data collected during two current meter deployments at site C.

Current meter deployment:	CM318	CM379
Near surface current speeds (cm s^{-1})		
Minimum	1.9	0.5
Median (50th percentile)	13.1	10.1
Mean	13.6	10.7
75th percentile	17.4	15.0
Maximum	30.0	28.6
Mid-depth current speeds (cm s^{-1})		
Minimum	1.2	0.6
Median (50th percentile)	11.6	11.9
Mean	12.0	11.8
75th percentile	15.3	16.2
Maximum	30.0	28.3
Near-bottom current speeds (cm s^{-1})		
Minimum	1.8	0.1
Median (50th percentile)	11.5	9.4
Mean	12.1	9.8
75th percentile	15.3	12.8
Maximum	32.3	29.9
% of near-bottom records >9.5 cm s^{-1}	66	49

Table 19. Estimated areas of impacted seafloor at site C using a simple model and mid-depth current speed data from two current meter deployments (CM318 and CM379) near the site.

Particle type	Mid-depth current speed	Impacted seafloor area (m^2)	
		CM318	CM379
Feed pellets	Median	53,500	54,200
	Maximum	99,300	95,100
Feces	Median	121,100	124,000
	Maximum	351,500	325,500

Table 20. DEPOMOD mass balance calculations at site C. The rate of waste released from the farm was calculated from the feeding rate and the estimated rate of waste production per unit of feed, based on the feed and feces characteristics. The percent of waste deposition within the model domain (1 × 1 km) was calculated from the predicted waste deposition rates within each model grid cell.

Sediment sampling date	CM	Total feed rate (kg d^{-1})	Waste produced per kg feed (kg)	Waste produced (kg C d^{-1})	% of waste within the DEPOMOD domain	
					Resuspension off	Resuspension on
Sep 06	318	14,218	0.044	626	100	<1
	379	14,218	0.044	626	100	6

Table 21. Estimated areas of seafloor within EMP classifications at site C, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during September 2006 and current velocity data from two current meter deployments (CM318 and CM379) at locations near the site (see Fig. 10). The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Contour area (m^2)		Change due to resuspension	
		Resuspension off	Resuspension on	Area (m^2)	% change
CM318					
Oxic A	0.3-1.0	35,800	0	-35,800	-100
Oxic B	1.0-2.0	18,000	0	-18,000	-100
Hypoxic A	2.0-5.0	28,500	0	-28,500	-100
Hypoxic B	5.0-7.5	13,000	0	-13,000	-100
Hypoxic C	7.5-10.0	16,500	0	-16,500	-100
Anoxic	>10.0	20,700	0	-20,700	-100
>5 g C m^{-2} d^{-1}	>5.0	50,200	0	-50,200	-100
CM379					
Oxic A	0.3-1.0	33,100	12,700	-20,400	-62
Oxic B	1.0-2.0	17,300	7,900	-9,400	-54
Hypoxic A	2.0-5.0	26,700	5,500	-21,200	-79
Hypoxic B	5.0-7.5	13,600	200	-13,400	-99
Hypoxic C	7.5-10.0	12,600	0	-12,600	-100
Anoxic	>10.0	22,400	0	-22,400	-100
>5 g C m^{-2} d^{-1}	>5.0	48,600	200	-48,400	-100

Table 22. Maximum predicted carbon deposition rates and maximum observed sediment sulfide concentrations at site C. The maximum deposition rate is the highest of all predicted carbon deposition rates within the DEPOMOD domain. The maximum sediment sulfide concentration is the highest of the sample location means (from triplicate subsamples).

	Maximum predicted deposition rate (g C m^{-2} d^{-1})		Maximum sediment sulfide concentration (μM)
CM	Resuspension off	Resuspension on	
318	17.9	0.1	6,670
379	20.2	6.8	

Table 23. Estimated areas of seafloor within EMP classifications at site C, based on the sulfide concentration in sediment samples collected in 12 September 2006 (Chang et al. 2011). The Oxic A category excludes areas where the sulfide concentration was below the estimated background concentration of 300 μM.

Site classification	Sediment sulfide concentration (μM)	Seafloor area (m^2)
Oxic A	300 – 750	50,700
Oxic B	750 – 1,500	45,100
Hypoxic A	1,500 – 3,000	26,900
Hypoxic B	3,000 – 4,500	2,300
Hypoxic C	4,500 – 6,000	1,800
Anoxic	>6,000	700
≥Hypoxic B	>3,000	4,800

Table 24. Dates, durations, and depth layers for current meter deployments at site D. Current velocities were measured using Acoustic Doppler Current Profilers deployed about one meter above the seafloor. The average depth from the water surface to the seafloor was estimated from CHS bathymetry and tidal data.

CM	Start date	End date	Duration (d)	Average depth from surface to seafloor (m)	Depth layer	
383	8 Jun 09	7 Aug 09	61	15.6	Near surface:	3.5 m below surface
					Mid-depth:	7.6 m above seafloor
					Near bottom:	4.6 m above seafloor
409	21 Sep 09	17 Nov 09	58	17.5	Near surface:	3.5 m below surface
					Mid-depth:	8.7 m above seafloor
					Near bottom:	4.7 m above seafloor

Table 25. Summary of water current speed data collected during two current meter deployments at site D.

Current meter deployment:	CM383	CM409
Near surface current speeds (cm s^{-1})		
Minimum	0.1	0.1
Median (50th percentile)	4.4	7.8
Mean	5.3	8.6
75th percentile	6.8	11.7
Maximum	34.8	39.3
Mid-depth current speeds (cm s^{-1})		
Minimum	0.0	0.1
Median (50th percentile)	4.5	8.1
Mean	5.0	8.8
75th percentile	6.6	12.1
Maximum	22.8	47.7
Near-bottom current speeds (cm s^{-1})		
Minimum	0.1	0.3
Median (50th percentile)	5.7	9.5
Mean	5.9	10.1
75th percentile	7.8	13.3
Maximum	19.1	34.9
% of near-bottom records >9.5 cm s^{-1}	11	50

Table 26. Estimated areas of impacted seafloor at site D using a simple model and mid-depth current speed data from two current meter deployments (CM383 and CM409) near the site.

Particle type	Mid-depth current speed	Impacted seafloor area (m^2) CM383	CM409
Feed pellets	Median	17,200	25,600
	Maximum	59,200	130,100
Feces	Median	41,700	72,100
	Maximum	213,000	521,400

Table 27. DEPOMOD mass balance calculations at site D. The rate of waste released from the farm was calculated from the feeding rate and the estimated rate of waste production per unit of feed, based on the feed and feces characteristics. The percent of waste deposition within the model domain (1 × 1 km) was calculated from the predicted waste deposition rates within each model grid cell.

					% of waste within the DEPOMOD domain	
Sediment sampling date	CM	Total feed rate (kg d^{-1})	Waste produced per kg feed (kg)	Waste produced (kg C d^{-1})	Resuspension off	Resuspension on
Jul 07	383	4,927	0.044	217	100	79
	409	4,927	0.044	217	100	15

Table 28. Estimated areas of seafloor within EMP classifications at site D, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during the 30 d prior to 24 July 2007 and current velocity data from two current meter deployments (CM383 and CM409) at locations near the site (see Fig. 16). The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

		Contour area (m^2)		Change due to resuspension	
Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Resuspension off	Resuspension on	Area (m^2)	% change
CM383					
Oxic A	0.3-1.0	21,100	13,100	-8,000	-38
Oxic B	1.0-2.0	10,900	7,900	-3,000	-28
Hypoxic A	2.0-5.0	13,800	10,600	-3,300	-23
Hypoxic B	5.0-7.5	4,500	3,600	-900	-20
Hypoxic C	7.5-10.0	2,800	2,300	-400	-18
Anoxic	>10.0	5,400	4,600	-800	-15
>5 g C m^{-2} d^{-1}	>5.0	12,700	10,500	-2,100	-17
CM409					
Oxic A	0.3-1.0	38,400	11,200	-27,200	-71
Oxic B	1.0-2.0	19,900	4,300	-15,600	-78
Hypoxic A	2.0-5.0	20,100	4,100	-16,100	-80
Hypoxic B	5.0-7.5	5,000	500	-4,500	-90
Hypoxic C	7.5-10.0	2,500	100	-2,400	-96
Anoxic	>10.0	3,300	0	-3,300	-100
>5 g C m^{-2} d^{-1}	>5.0	10,800	600	-10,200	-94

Table 29. Maximum predicted carbon deposition rates and maximum observed sediment sulfide concentrations at site D. The maximum deposition rate is the highest of all predicted carbon deposition rates within the DEPOMOD domain. The maximum sediment sulfide concentration is the highest of the sample location means (from triplicate subsamples).

	Maximum predicted deposition rate (g C m^{-2} d^{-1})		Maximum sediment sulfide concentration (µM)
CM	Resuspension off	Resuspension on	
383	35.0	33.9	4,823
409	21.8	10.0	

Table 30. Estimated areas of seafloor within EMP classifications at site D, based on the sulfide concentration in sediment samples collected on 24 July 2007 (Chang et al. 2011). The Oxic A category excludes areas where the sulfide concentration was below the estimated background concentration of 300 µM.

Site Classification	Sediment sulfide concentration (µM)	Seafloor area (m^2)
Oxic A	300 – 750	48,900
Oxic B	750 – 1,500	40,300
Hypoxic A	1,500 – 3,000	19,000
Hypoxic B	3,000 – 4,500	3,200
Hypoxic C	4,500 – 6,000	500
Anoxic	>6,000	0
≥Hypoxic B	>3,000	3,700

Table 31. Dates, durations, and depths for current meter deployments at site G. Current velocities were measured at the deployment depth using InterOcean S4 current meters. The average depth from the water surface to the seafloor was estimated from CHS bathymetry and tidal data.

CM	Start date	End date	Duration (d)	Average depth from surface to seafloor (m)	CM depth
119	6 Jul 01	12 Aug 01	37	19.0	6 m above seafloor
120	6 Jul 01	10 Aug 01	35	17.8	6 m above seafloor

Table 32. Summary of water current speed data collected during two current meter deployments at site G.

Current meter deployment:	CM119	CM120
Current speeds at 6 m above the seafloor (cm s^{-1})		
Minimum	0.0	0.0
Median (50th percentile)	2.6	2.5
Mean	2.9	2.9
75th percentile	4.2	4.1
Maximum	9.8	9.9
% of records >9.5 cm s^{-1}	<1	<1

Table 33. Estimated areas of impacted seafloor at site G using a simple model and current speed measured 6 m above the seafloor during two current meter deployments (CM119 and CM120) in the vicinity of the farm.

		Impacted seafloor area (m^2)	
Particle type	Current speed	CM119	CM120
Feed pellets	Median	11 200	11,000
	Maximum	27,300	27,500
Feces	Median	26,300	25,800
	Maximum	60,500	61,000

Table 34. DEPOMOD mass balance calculations at site G. The rate of waste released from the farm was calculated from the feeding rate and the estimated rate of waste production per unit of feed, based on the feed and feces characteristics. The percent of waste deposition within the model domain (1 × 1 km) was calculated from the predicted waste deposition rates within each model grid cell. Sediment sampling was conducted on 8 September 2010.

Feed period	CM	Total feed rate (kg d^{-1})	Waste produced per kg feed (kg)	Waste produced (kg C d^{-1})	% of waste within the DEPOMOD domain: Resuspension off	% of waste within the DEPOMOD domain: Resuspension on
Aug-Sep 10	119	283	0.044	12	100	69
	120	283	0.044	12	100	88
Jul 10	119	3,534	0.044	155	100	96
	120	3,534	0.044	155	100	99

Table 35. Estimated areas of seafloor within EMP classifications at site G, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during 8 August-11 September 2010 and current velocity data from two current meter deployments (CM119 and CM120) at locations near the site (see Fig. 22). The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Contour area (m^2): Resuspension off	Contour area (m^2): Resuspension on	Change due to resuspension: Area (m^2)	Change due to resuspension: % change
CM119					
Oxic A	0.3-1.0	17,300	11,300	-5,900	-35
Oxic B	1.0-2.0	600	0	-600	-100
Hypoxic A	2.0-5.0	0	0	0	0
Hypoxic B	5.0-7.5	0	0	0	0
Hypoxic C	7.5-10.0	0	0	0	0
Anoxic	>10.0	0	0	0	0
>5 g C m^{-2} d^{-1}	>5.0	0	0	0	0
CM120					
Oxic A	0.3-1.0	17 200	15,600	-1,600	-9
Oxic B	1.0-2.0	600	300	-300	-50
Hypoxic A	2.0-5.0	0	0	0	0
Hypoxic B	5.0-7.5	0	0	0	0
Hypoxic C	7.5-10.0	0	0	0	0
Anoxic	>10.0	0	0	0	0
>5 g C m^{-2} d^{-1}	>5.0	0	0	0	0

Table 36. Estimated areas of seafloor within EMP classifications at site G, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during July 2010 and current velocity data from two current meter deployments (CM119 and CM120) at locations near the site. The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Contour area (m^2)		Change due to resuspension	
		Resuspension off	Resuspension on	Area (m^2)	% change
CM119					
Oxic A	0.3-1.0	8,000	6,400	-1,600	-20
Oxic B	1.0-2.0	4,200	3,800	-400	-10
Hypoxic A	2.0-5.0	10,300	10,700	400	4
Hypoxic B	5.0-7.5	8,600	8,200	-400	-5
Hypoxic C	7.5-10.0	4,000	3,800	-200	-5
Anoxic	>10.0	1,400	1,300	-200	-7
>5 g C m^{-2} d^{-1}	>5.0	14,000	13,300	-800	-5
CM120					
Oxic A	0.3-1.0	7,700	7,000	-700	-9
Oxic B	1.0-2.0	4,300	4,200	-100	-2
Hypoxic A	2.0-5.0	10,200	10,300	100	1
Hypoxic B	5.0-7.5	8,700	8,600	-100	-1
Hypoxic C	7.5-10.0	4,100	4,000	0	-2
Anoxic	>10.0	1,400	1,300	-100	-7
>5 g C m^{-2} d^{-1}	>5.0	14,200	13,900	-200	-2

Table 37. Maximum predicted carbon deposition rates and maximum observed sediment sulfide concentrations at site G. The maximum deposition rate is the highest of all predicted carbon deposition rates within the DEPOMOD domain. The maximum sediment sulfide concentration is the highest of the sample location means (from triplicate subsamples). DEPOMOD was run using two feed rates: August-September 2010 and July 2010.

		Maximum predicted deposition rate (g C m^{-2} d^{-1})		
Feed rate period	CM	Resuspension off	Resuspension on	Maximum sediment sulfide concentration (µM)
Aug-Sep 10	119	1.4	1.3	9,087
	120	1.4	1.3	
Jul 10	119	15.2	15.1	9,087
	120	14.7	14.6	

Table 38. Estimated areas of seafloor within EMP classifications at site G, based on the sulfide concentration in EMP Tier 2 monitoring samples collected on 8 September 2010 (data collected by Silk Stevens Ltd.). The Oxic A category excludes areas where the sulfide concentration was below the estimated background concentration of 300 µM.

Site classification	Sediment sulfide concentration (µM)	Seafloor area (m^2)
Oxic A	300 – 750	0
Oxic B	750 – 1,500	2,300
Hypoxic A	1,500 – 3,000	5,800
Hypoxic B	3,000 – 4,500	6,100
Hypoxic C	4,500 – 6,000	7,900
Anoxic	>6,000	3,500
≥Hypoxic B	>3,000	17,500

Table 39. Dates, durations, and depth layers for current meter deployments at site H. Current velocities were measured using Acoustic Doppler Current Profilers deployed about one meter above the seafloor. The average depth from the water surface to the seafloor was estimated from CHS bathymetry and tidal data.

CM	Start date	End date	Duration (d)	Average depth from surface to seafloor (m)	Depth layer	
381	7 Jun 09	6 Aug 09	60	28.6	Near surface:	2.5 m below surface
					Mid-depth:	13.6 m above seafloor
					Near bottom:	3.6 m above seafloor
389	9 Jun 09	7 Aug 09	59	19.2	Near surface:	2.5 m below surface
					Mid-depth:	9.6 m above seafloor
					Near bottom:	4.6 m above seafloor

Table 40. Summary of water current speed data collected during two current meter deployments at site H.

Current meter deployment:	CM381	CM389
Near surface current speeds (cm s^{-1})		
Minimum	0.4	0.6
Median (50th percentile)	6.5	7.1
Mean	7.7	8.0
75th percentile	9.9	10.8
Maximum	31.4	20.9
Mid-depth current speeds (cm s^{-1})		
Minimum	0.7	0.5
Median (50th percentile)	8.0	5.4
Mean	8.4	5.9
75th percentile	10.9	7.7
Maximum	24.7	19.1
Near-bottom current speeds (cm s^{-1})		
Minimum	0.7	0.5
Median (50th percentile)	8.2	5.9
Mean	9.1	6.6
75th percentile	12.3	8.8
Maximum	31.2	21.1
% of near-bottom records >9.5 cm s^{-1}	43	22

Table 41. Estimated areas of impacted seafloor at site H using a simple model and mid-depth current speed data from two current meter deployments (CM381 and CM389) near the site.

Particle type	Mid-depth current speed	Impacted seafloor area (m^2)	
		CM381	CM389
Feed pellets	Median	53,800	46,600
	Maximum	102,100	85,000
Feces	Median	110,900	83,400
	Maximum	353,500	259,000

Table 42. DEPOMOD mass balance calculations at site H. The rate of waste released from the farm was calculated from the feeding rate and the estimated rate of waste production per unit of feed, based on the feed and feces characteristics. The percent of waste deposition within the model domain (2 × 2 km) was calculated from the predicted waste deposition rates within each model grid cell.

Sediment sampling date	CM	Total feed rate (kg d^{-1})	Waste produced per kg feed (kg)	Waste produced (kg C d^{-1})	% of waste within the DEPOMOD domain	
					Resuspension off	Resuspension on
Sep 09	381	14,485	0.044	637	100	22
	389	14,485	0.044	637	100	64

Table 43. Estimated areas of seafloor within EMP classifications at site H, based on DEPOMOD predictions of carbon deposition rates using the average daily feed rates per cage during 16 August–12 September 2009 and current velocity data from two current meter deployments (CM381 and CM389) at locations near the site (Fig. 29). The model was run with resuspension turned off and on. The Oxic A category excludes areas where predicted carbon deposition rates were below the estimated background rate of 0.3 g C m^{-2} d^{-1}.

Site classification	Carbon deposition rate (g C m^{-2} d^{-1})	Contour area (m^2)		Change due to resuspension	
		Resuspension off	Resuspension on	Area (m^2)	% change
CM381					
Oxic A	0.3-1.0	16,400	11,700	-4,700	-29
Oxic B	1.0-2.0	10,800	14,700	3,900	36
Hypoxic A	2.0-5.0	15,500	23,300	7,700	50
Hypoxic B	5.0-7.5	8,000	3,700	-4,300	-54
Hypoxic C	7.5-10.0	8,400	900	-7,500	-89
Anoxic	>10.0	32,400	200	-32.200	-99
>5 g C m^{-2} d^{-1}	>5.0	48,800	4,800	-44,000	-90
CM389					
Oxic A	0.3-1.0	24 200	10,800	-13,400	-55
Oxic B	1.0-2.0	12,300	7,100	-5 200	-42
Hypoxic A	2.0-5.0	15,700	13,000	-2,800	-17
Hypoxic B	5.0-7.5	8 200	13,300	5,100	62
Hypoxic C	7.5-10.0	8,100	14,800	6,700	83
Anoxic	>10.0	33,300	11,100	-22,200	-67
>5 g C m^{-2} d^{-1}	>5.0	49,600	39,200	-10,400	-21

Table 44. Maximum predicted carbon deposition rates and maximum observed sediment sulfide concentrations at site H. The maximum deposition rate is the highest of all predicted carbon deposition rates within the DEPOMOD domain. The maximum sediment sulfide concentration is the highest of the sample location means (from triplicate subsamples).

	Maximum predicted deposition rate (g C m^{-2} d^{-1})		Maximum sediment sulfide concentration (µM)
CM	Resuspension off	Resuspension on	
381	27.0	13.6	8,703
389	20.1	18.4	

Table 45. Estimated areas of seafloor within EMP classifications at site H, based on the sulfide concentration in EMP Tier 2 monitoring samples collected on 11-15 September 2009 (data collected by Dominator Marine Services Inc.). The Oxic A category excludes areas where the sulfide concentration was below the estimated background concentration of 300 µM.

Site Classification	Sediment sulfide concentration (µM)	Seafloor area (m^2)
Oxic A	300 – 750	0
Oxic B	750 – 1,500	100
Hypoxic A	1,500 – 3,000	6,700
Hypoxic B	3,000 – 4,500	22,400
Hypoxic C	4,500 – 6,000	16,400
Anoxic	>6,000	14,700
≥Hypoxic B	>3,000	53,500

Table 46. Summary table comparing predicted and observed areas of elevated benthic impacts under salmon farms, using a simple model (dispersion of feed pellets, using median mid-depth current speed), DEPOMOD (resuspension off, predicted carbon deposition rate >5 g C m^{-2} d^{-1}), and observed sediment sulfide concentration (>3,000 µM). DEPOMOD predictions used average daily feed rate per cage during a four to five week period including the date of sediment sampling, except at site G, where DEPOMOD was also run using an earlier, higher feed rate (from July 2010).

			Area of elevated benthic impacts (m^2)		
Site	Sediment sampling date	Current meter	Simple model: feed pellets, median current speed	DEPOMOD: resuspension off, deposition rate >5 g C m^{-2} d^{-1}	Observed sediment sulfide concentration: >3,000 µM
A	Sep 05	324	33,300	26,700	32,200
		329	35,700	25,800	
		330	36,800	21,400	
A	May 06	324	33,300	32,300	17,000
		329	35,700	32,900	
		330	36,800	32,700	
C	Sep 06	318	53,500	50,200	4,800
		379	54,200	48,600	
D	Jul 07	383	17,200	12,700	3,700
		409	25,600	10,800	
G (Aug-Sep feed)	Sep 10	119	11,200	0	17,500
		120	11,000	0	
G (July feed)	Sep 10	119	11,200	14,000	17,500
		120	11,000	14,200	
H	Sep 09	381	53,800	48,800	53,500
		389	46,600	49,600	

Table 47. Regression equations for the linear relationship between predicted carbon deposition rate (DEPOMOD, resuspension off) and observed sediment sulfide concentration (see Fig. 44-50). DEPOMOD predictions used average daily feed rate per cage during a four to five week period including the date of sediment sampling, except at site G, where DEPOMOD was also run using an earlier, higher feed rate (from July 2010). Also shown are two equations for the relationship between these parameters from Hargrave (2010).

Source	Sediment sampling date	Feed rate period	CM	Intercept	Slope	r^2
Hargrave (2010)	–	–	–	-25.2	632	0.99
equations	–	–	–	62.2	487	0.82
Site A	Sep 05	Sep 05	324	1,702	224	0.14
			329	1,695	224	0.14
			330	1,849	159	0.07
Site A	May 06	May 06	324	1,046	82	0.09
			329	1,008	89	0.10
			330	921	104	0.13
Site C	Sep 06	Sep 06	318	407	133	0.29
			379	430	144	0.29
Site D	Jul 07	Jun-Jul 07	383	533	139	0.37
			409	587	134	0.30
Site G	Sep 10	Aug-Sep 10	119	1,968	5,363	0.15
			120	1,863	5,733	0.18
Site G	Sep 10	Jul 10	119	2,365	353	0.06
			120	1,837	458	0.09
Site H	Sep 09	Aug-Sep 09	381	6,145	-133	0.13
			389	5,841	-97	0.03

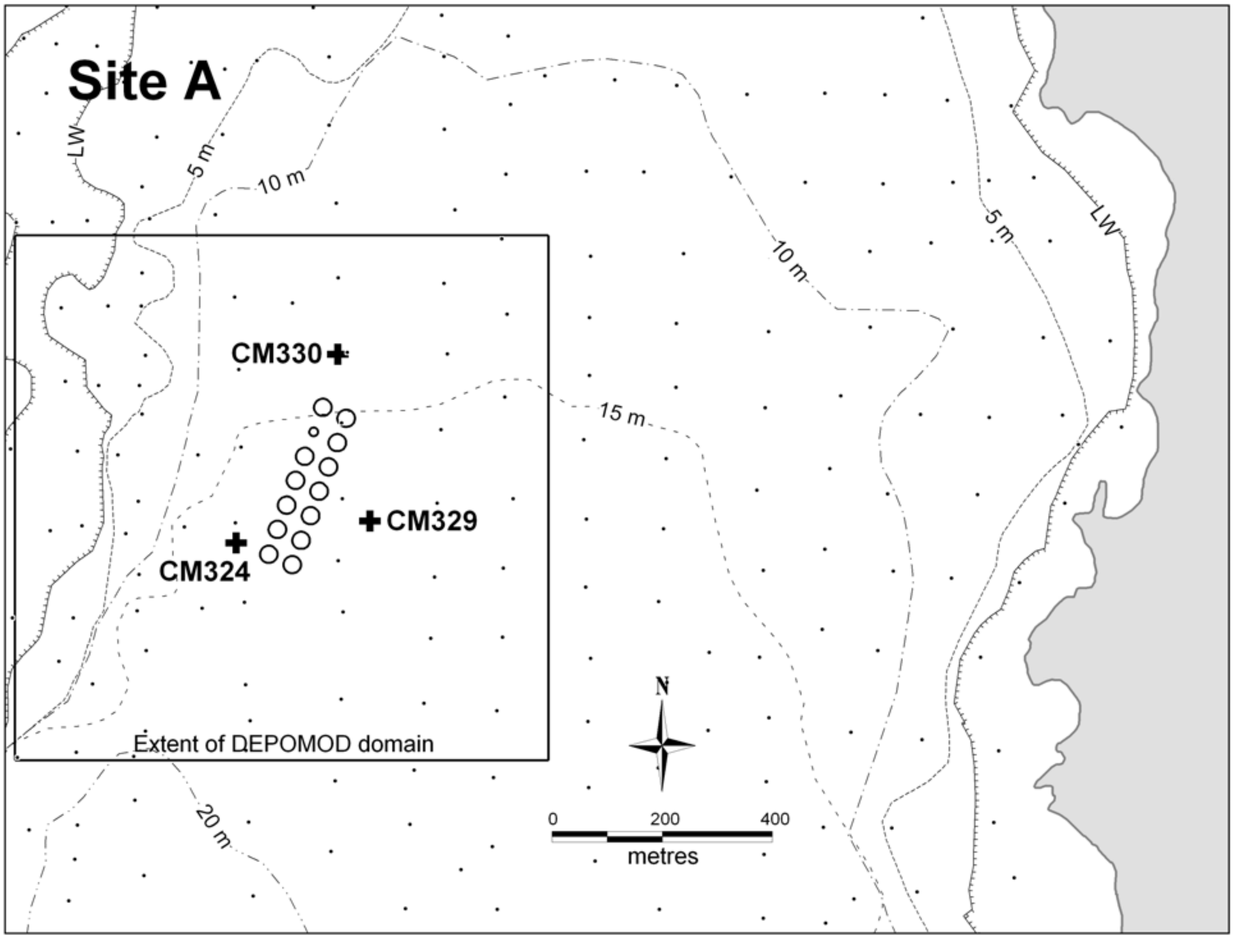


Fig. 1. Map of study site A, showing current meter locations (crosses), approximate cage locations and sizes (circles) at the time of sediment sampling (22 September 2005 and 24 May 2006), depth contours (relative to lowest normal tide, LW), and the extent of the DEPOMOD domain. Dots indicate locations of CHS depth soundings.

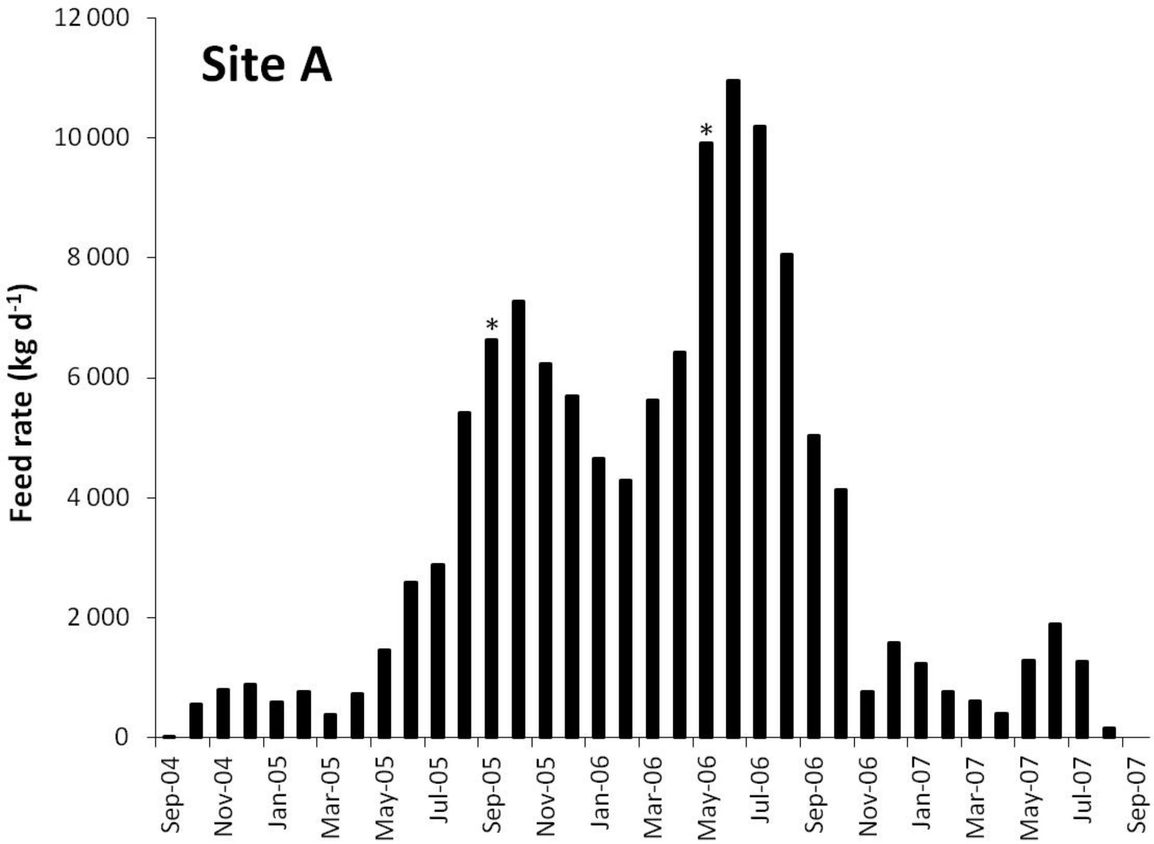


Fig. 2. Average daily feed rate per month at site A. Asterisks indicate the two months when sediment sampling was conducted.

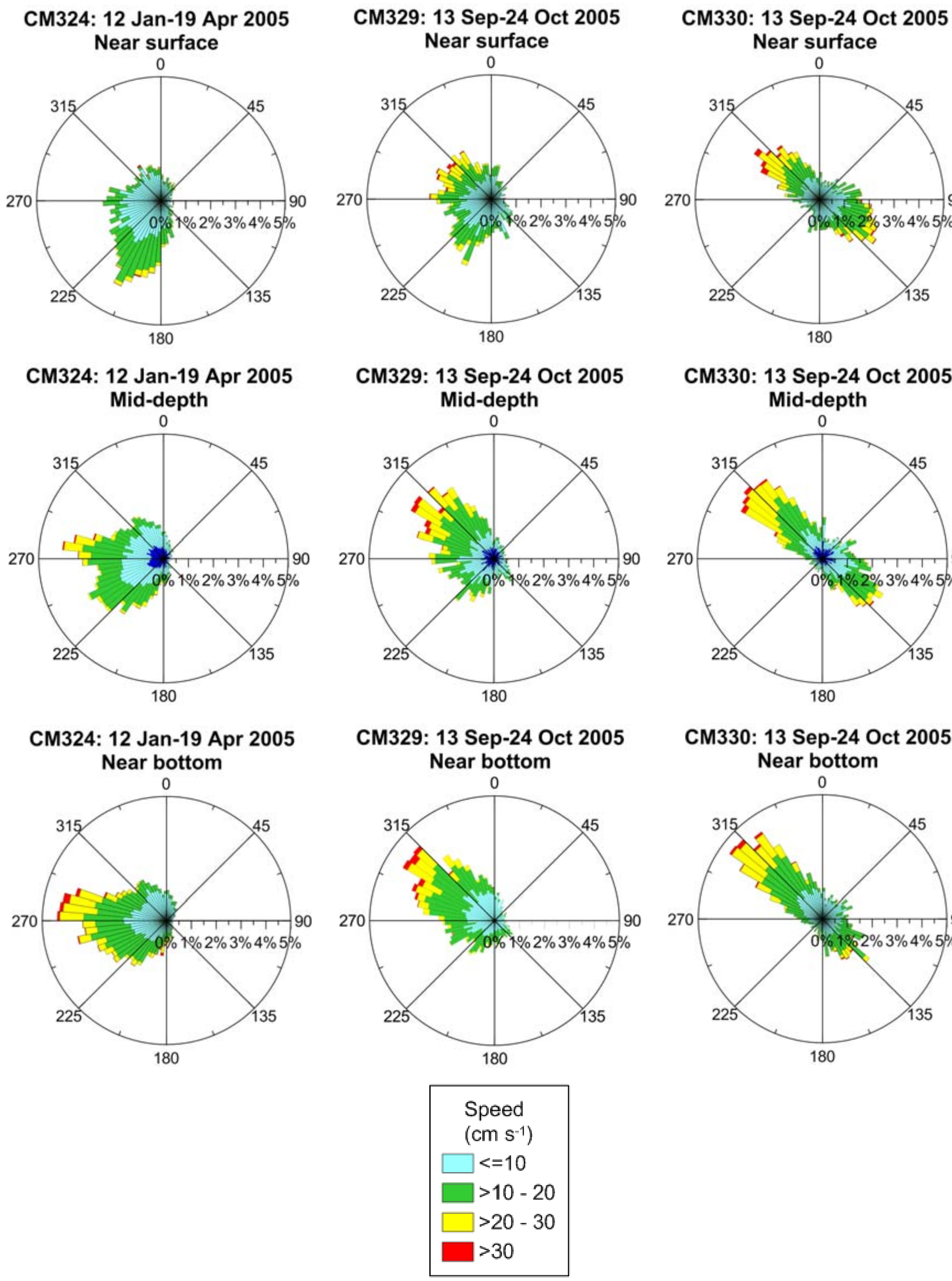


Fig. 3. Current velocity rose diagrams for three Acoustic Doppler Current Profiler current meter deployments at site A (see Fig. 1), near-surface, mid-depth, and near-bottom: CM324 (left column); CM329 (middle column); CM330 (right column).

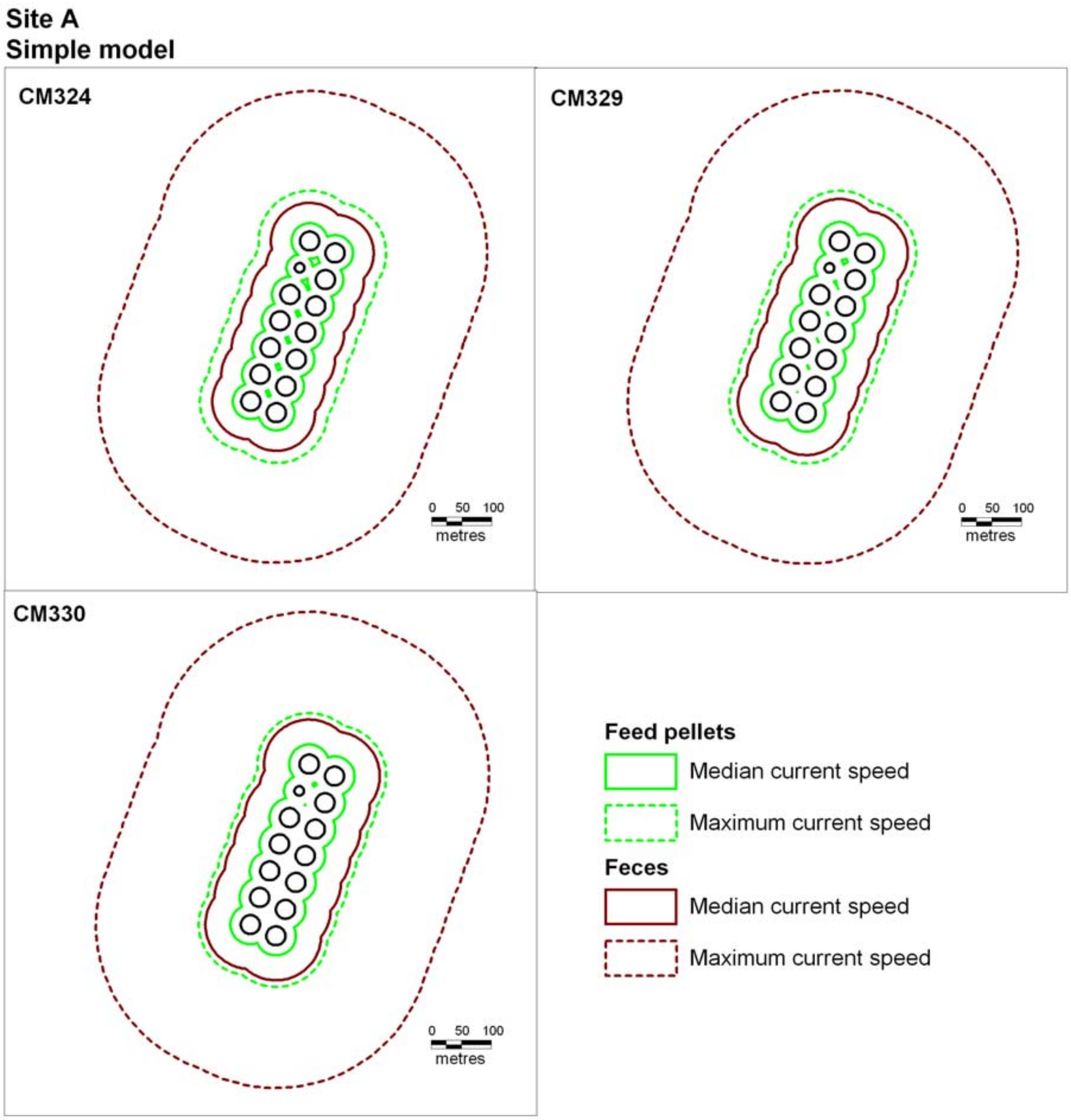


Fig. 4. Simple model estimates of area of seafloor impacted by feed pellets and feces released from cages at site A, using mid-depth current speeds from three current meter deployments near the farm: CM 324, MC 329, and CM 330. The estimates assume mean sinking rates of 11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces. Black circles indicate approximate cage locations and sizes.

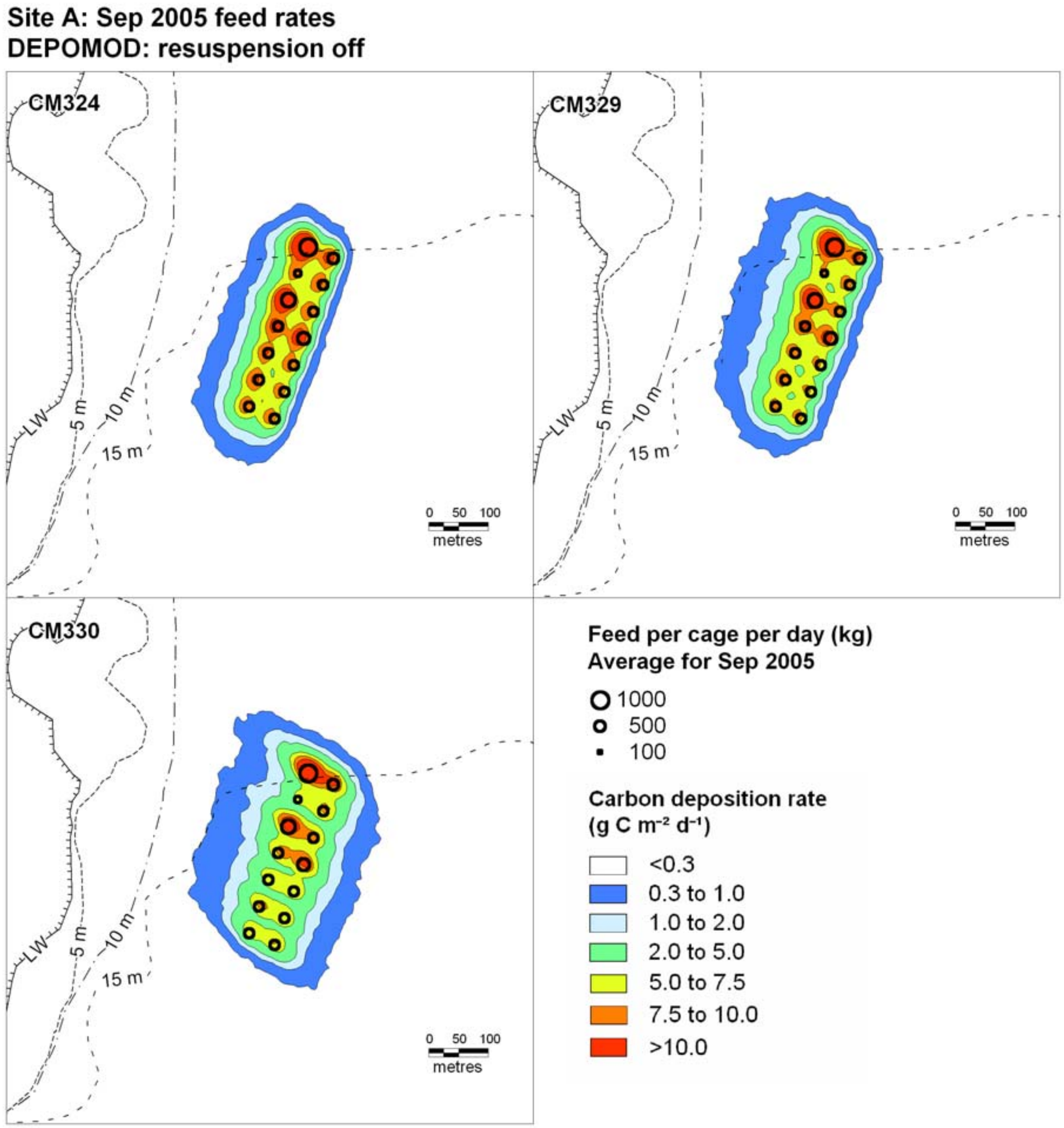


Fig. 5. Contour plots of DEPOMOD predicted carbon deposition rates at site A in September 2005, resuspension off. The model was run using three current meter deployments (CM324, CM329, and CM330) and average daily feed rates during September 2005. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005.

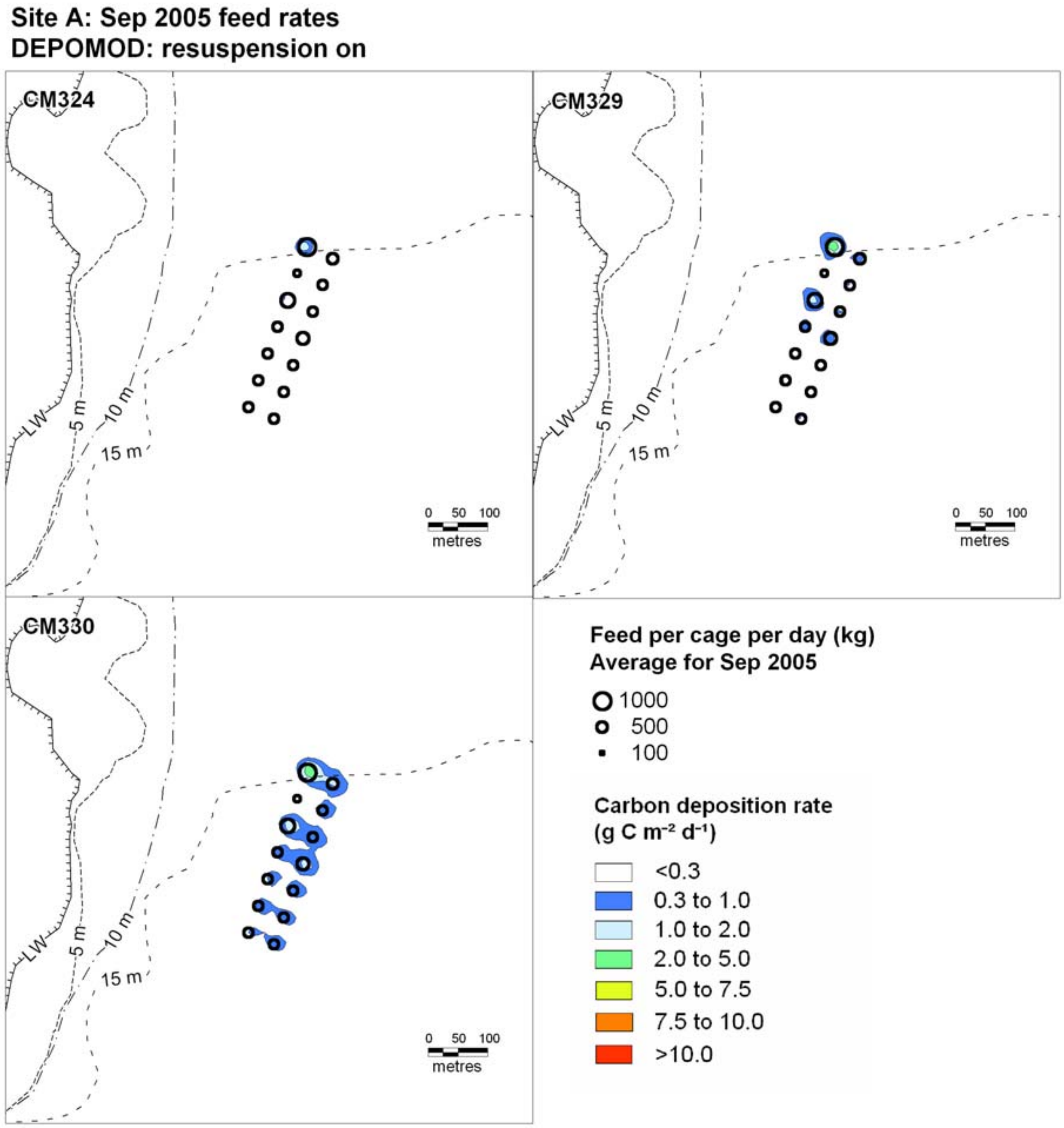


Fig. 6. Contour plots of DEPOMOD predicted carbon deposition rates at site A in September 2005, resuspension on. The model was run using three current meter deployments (CM324, CM329, and CM330) and average daily feed rates during September 2005. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005.

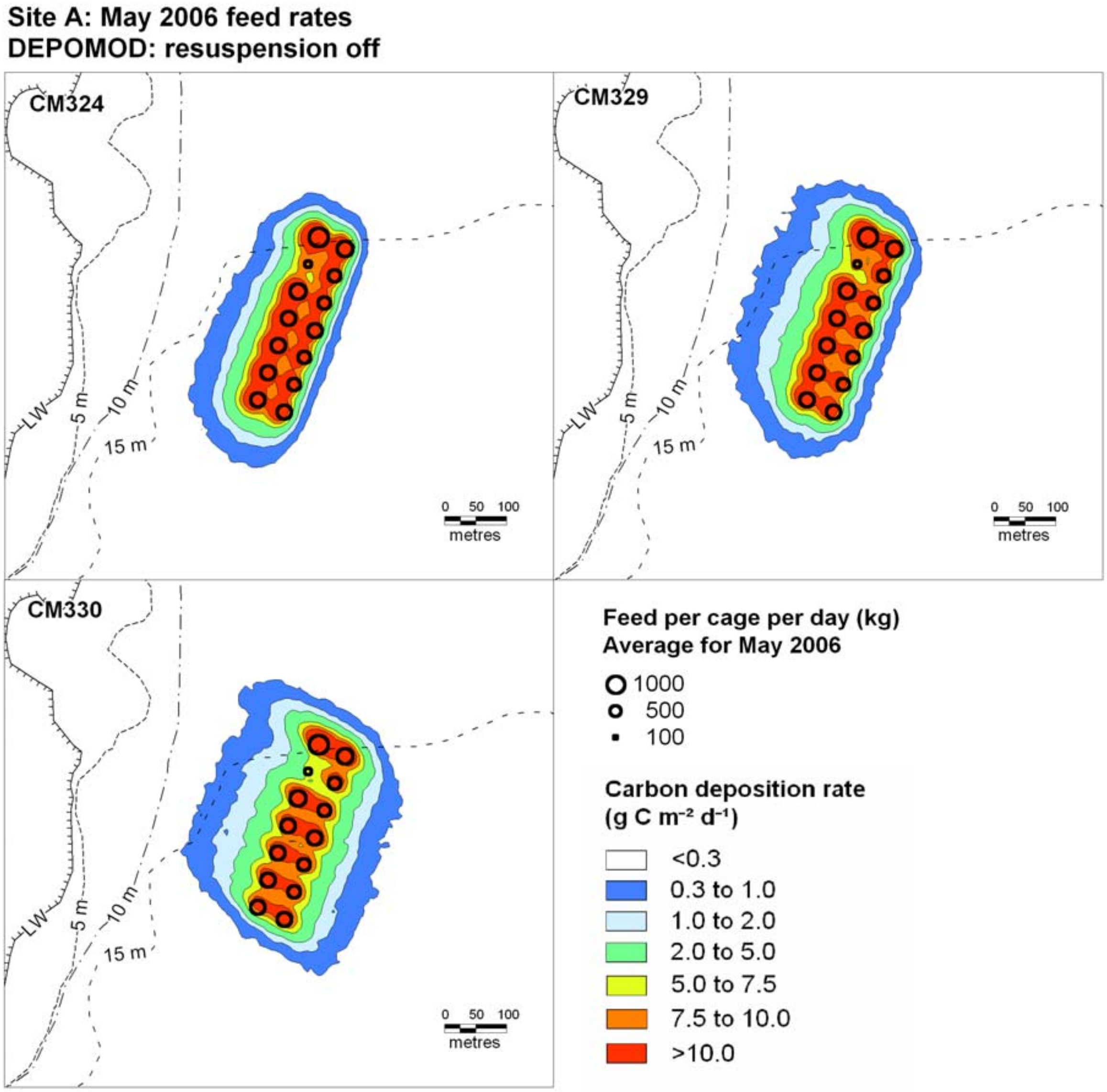


Fig. 7. Contour plots of DEPOMOD predicted carbon deposition rates at site A in May 2006, resuspension off. The model was run using three current meter deployments (CM324, CM329, and CM330) and average daily feed rates during May 2006. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during May 2006.

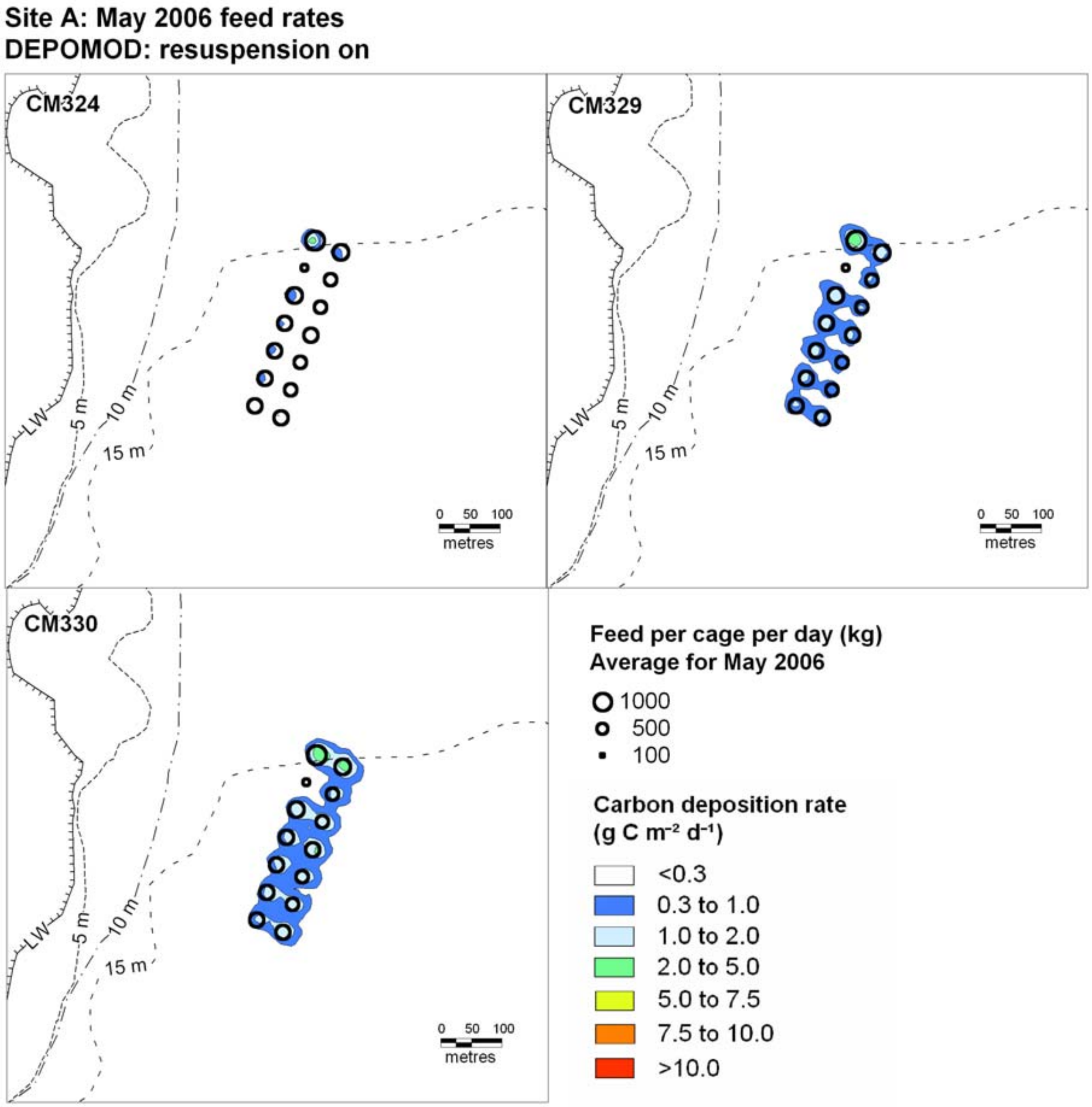


Fig. 8. Contour plots of DEPOMOD predicted carbon deposition rates at site A in May 2006, resuspension on. The model was run using three current meter deployments (CM324, CM329, and CM330) and average daily feed rates during May 2006. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during May 2006.

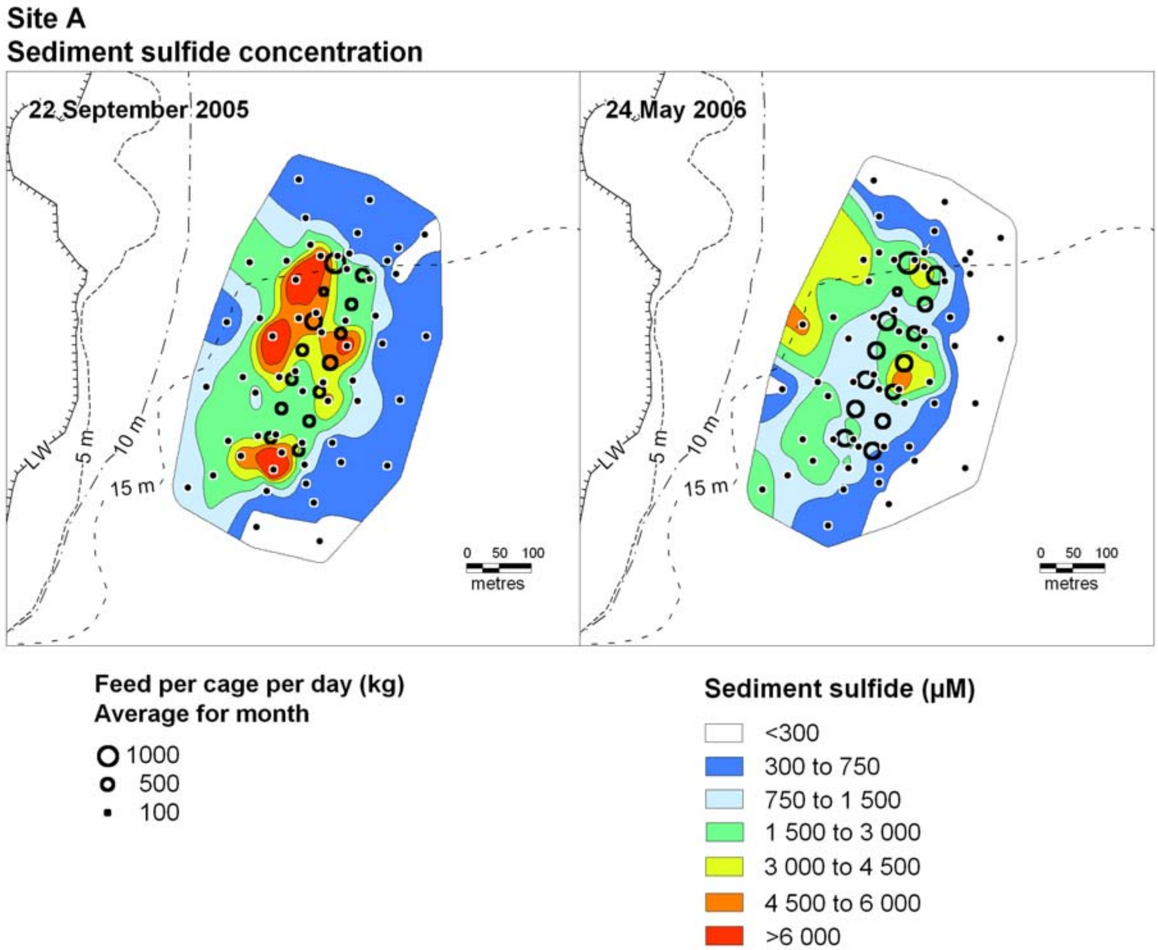


Fig. 9. Contour plots of sulfide levels at site A, derived from sediment grab samples taken on 22 September 2005 (left) and 24 May 2006 (right). Triplicate sulfide measurements were taken from grab samples taken at 57 locations on 22 September 2005 and 55 locations on 24 May 2006 (black dots). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005 (left) or May 2006 (right).

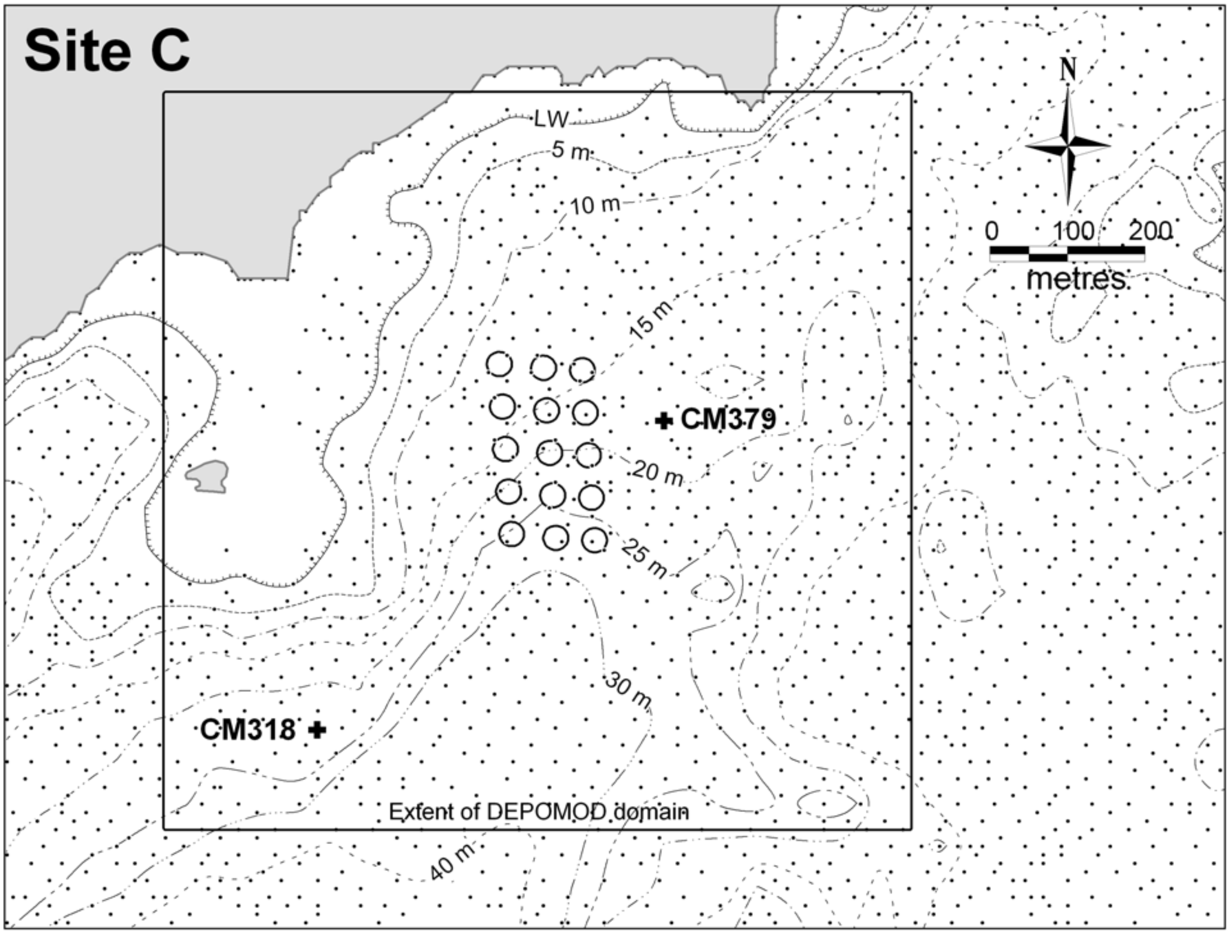


Fig. 10. Map of study site C, showing current meter locations (crosses), approximate cage locations and sizes (circles) at the time of sediment sampling, depth contours (relative to lowest normal tide, LW), and the extent of the DEPOMOD domain. Dots indicate locations of CHS depth soundings.

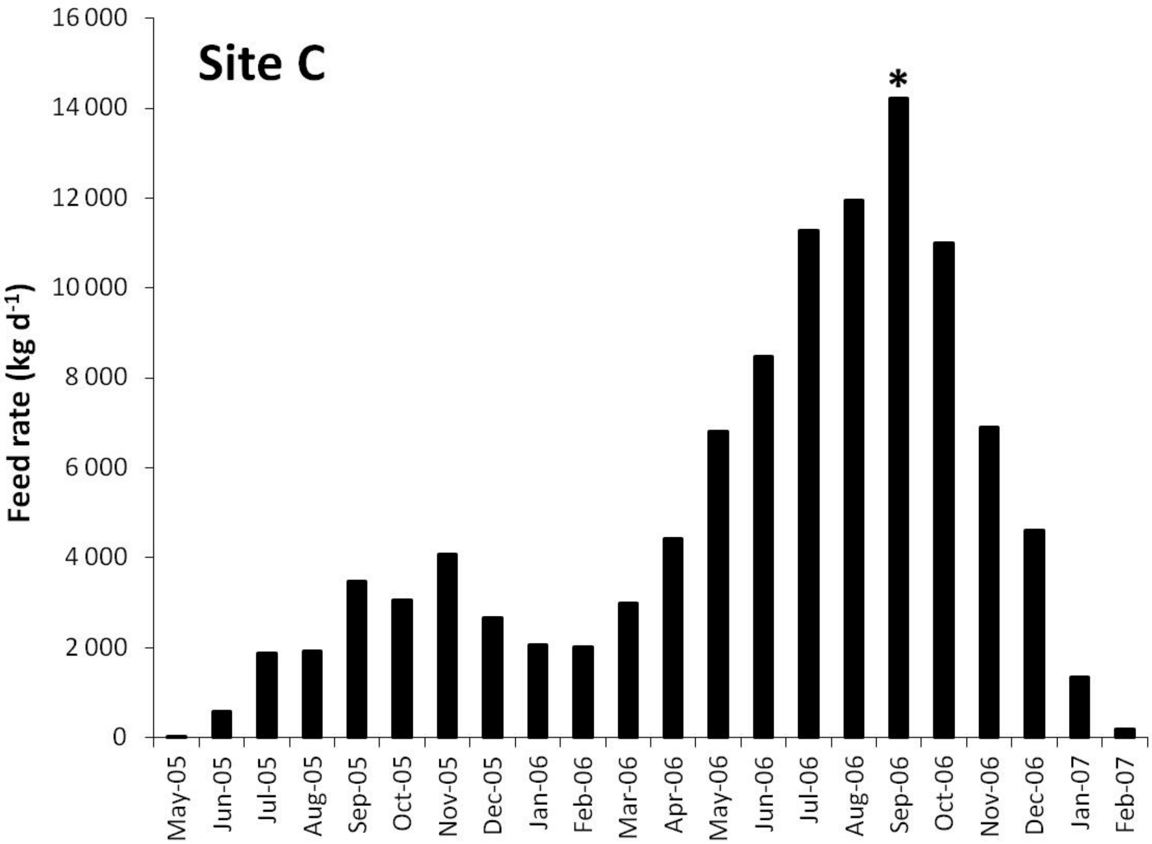


Fig. 11. Average daily feed rate per month at site C. The asterisk indicates the month when sediment sampling was conducted.

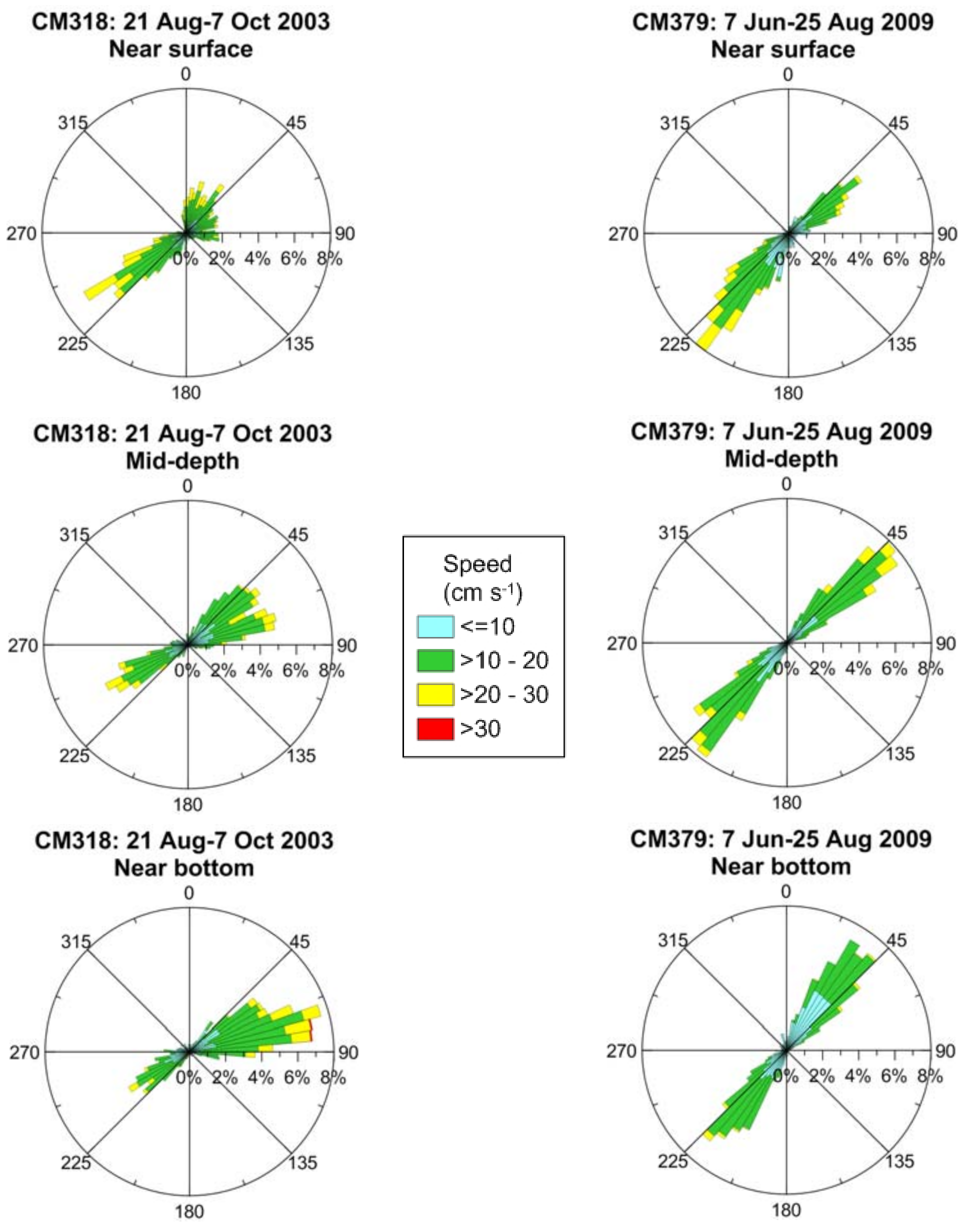


Fig. 12. Current velocity rose diagrams for two Acoustic Doppler Current Profiler current meter deployments at site C (see Fig. 10), near-surface, mid-depth, and near-bottom: CM318 (left column); CM379 (right column).

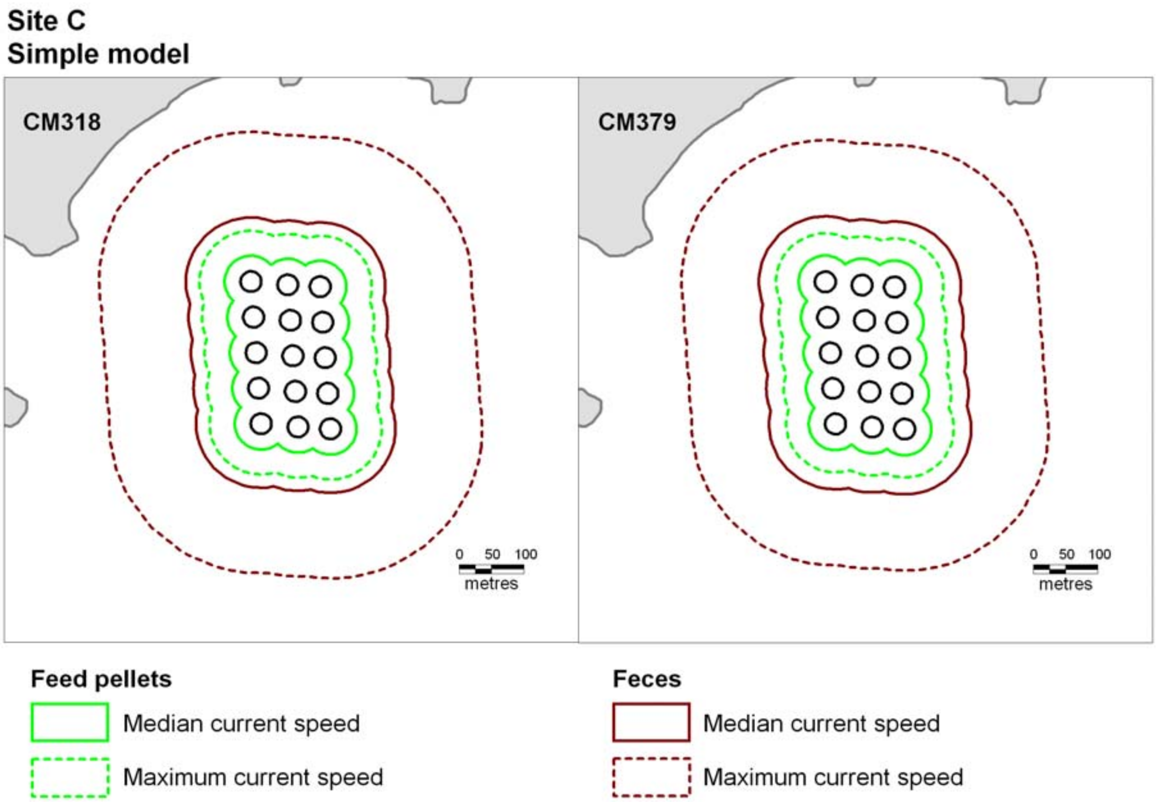


Fig. 13. Simple model estimates of area of seafloor impacted by feed pellets and feces released from cages at site C, using mid-depth current speeds from two current meter deployments near the farm: CM318 (left) and CM379 (right). The estimates assume mean sinking rates of 11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces. Black circles indicate approximate cage locations and sizes.

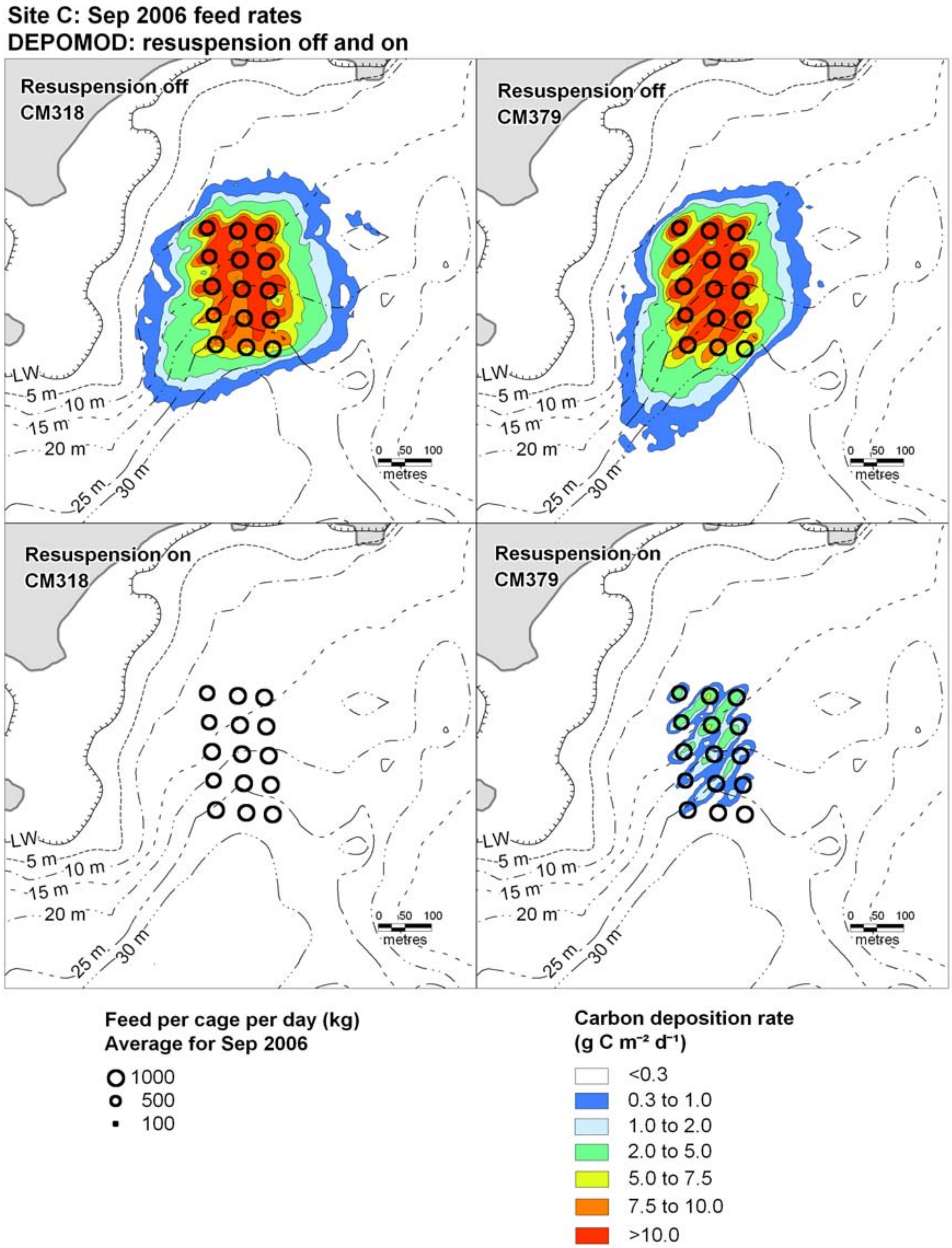


Fig. 14. Contour plots of DEPOMOD predicted carbon deposition rates at site C, resuspension off (top maps) and resuspension on (bottom maps). The model was run using two current meter deployments (CM318, left; CM379, right) and average daily feed rates during September 2006. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2006.

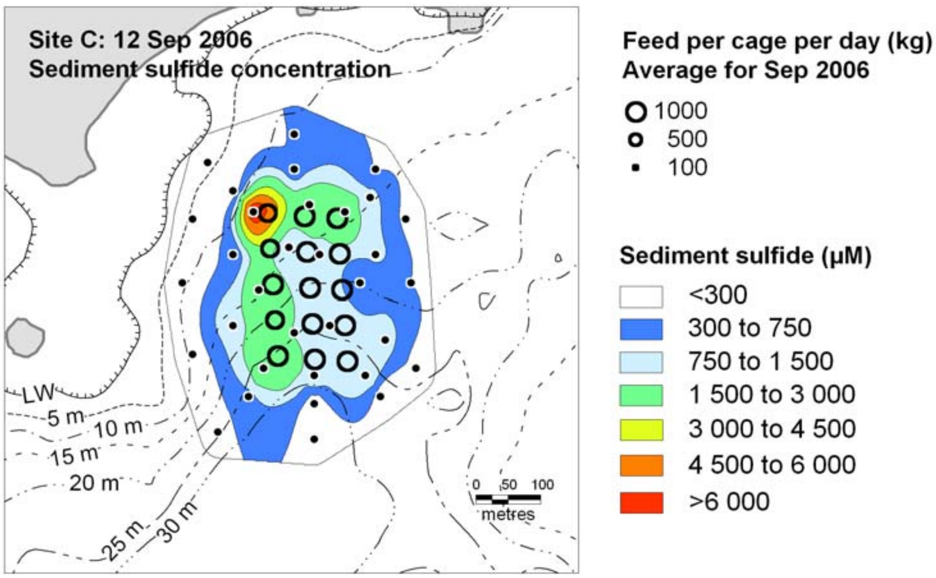


Fig. 15. Contour plots of sulfide levels at site C, derived from sediment grab samples taken on September 12, 2006. Triplicate sulfide measurements were taken from grab samples taken at 33 locations (black dots). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2006.

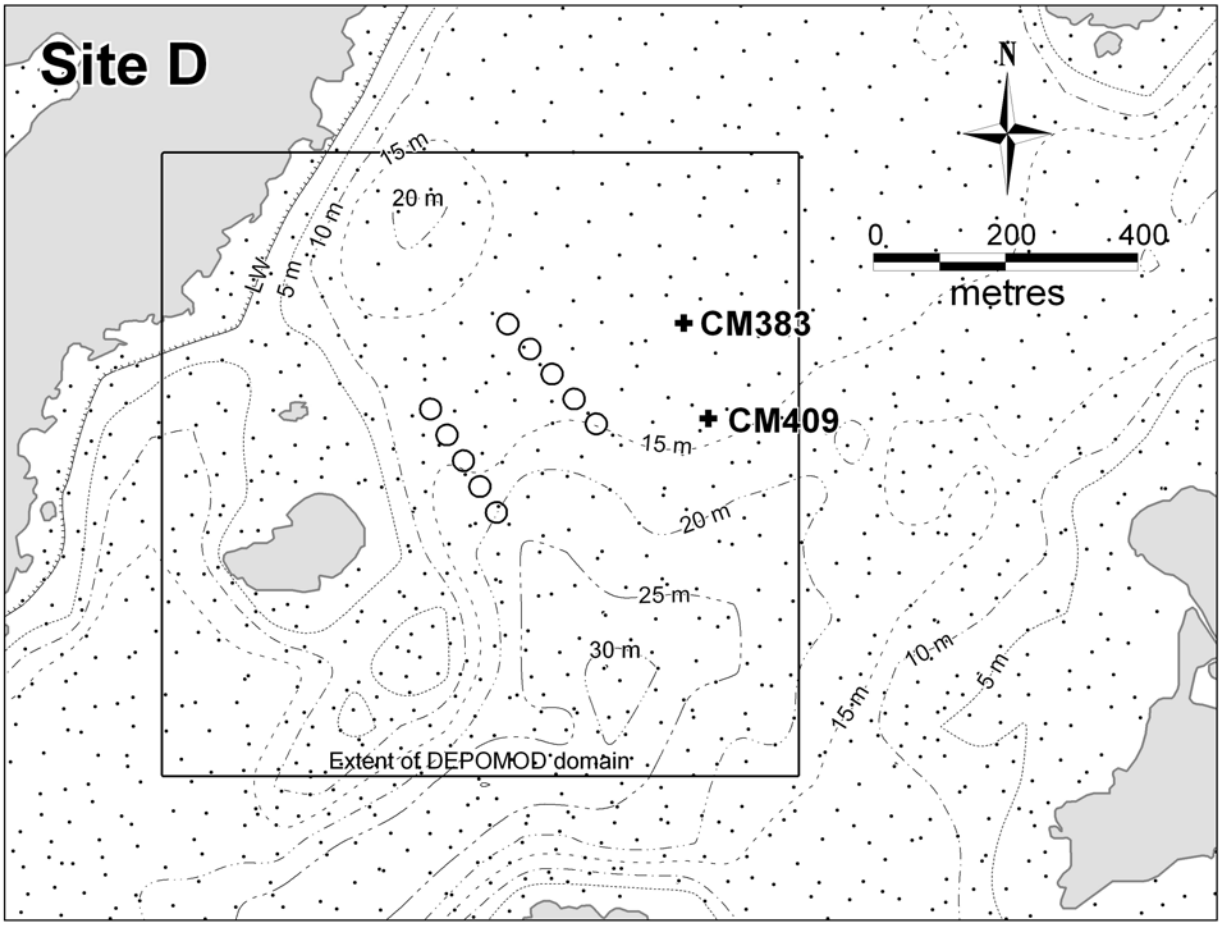


Fig. 16. Map of study site D, showing current meter locations (crosses), approximate cage locations and sizes (circles) at the time of sediment sampling, and depth contours (relative to lowest normal tide, LW), and the extent of the DEPOMOD domain. Dots indicate locations of CHS depth soundings.

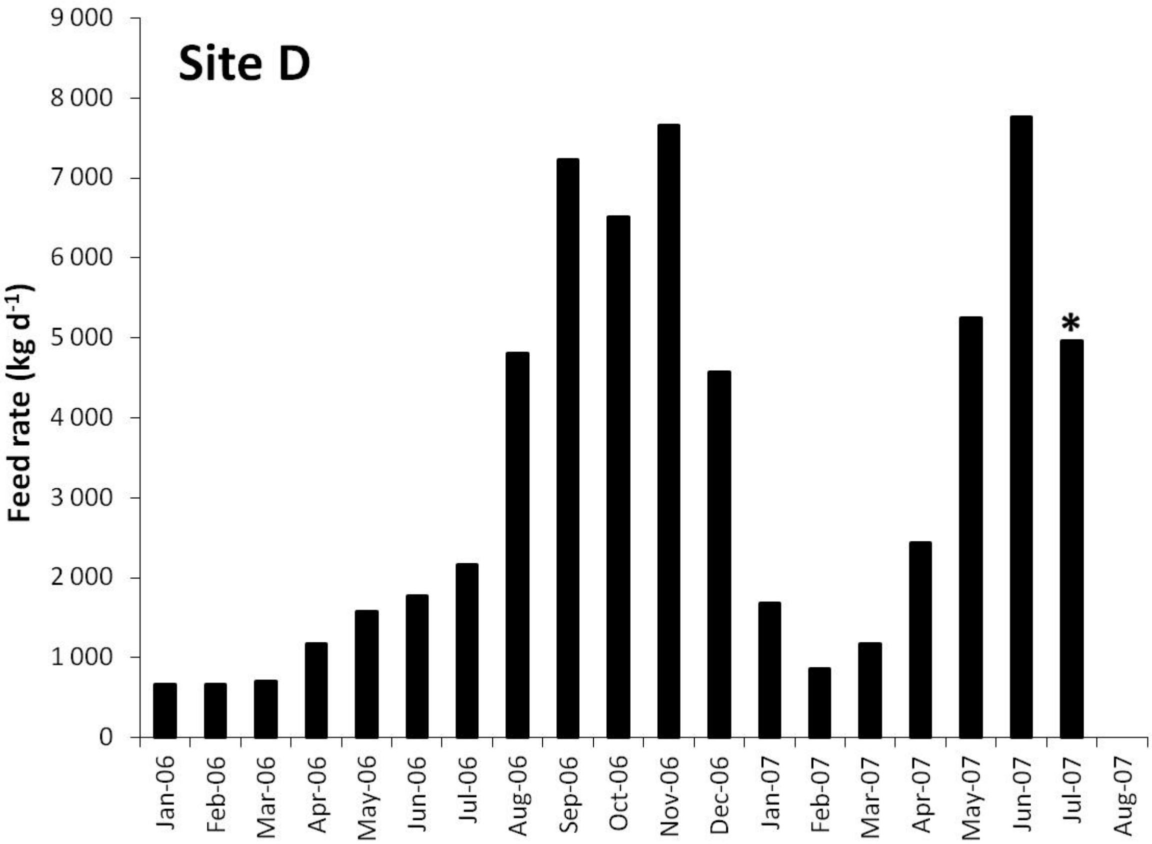


Fig. 17. Average daily feed rate per month at site D. Monthly feed rate data were not available for 2005 (the farm was stocked in the spring of 2005). The asterisk indicates the month when sediment sampling was conducted.

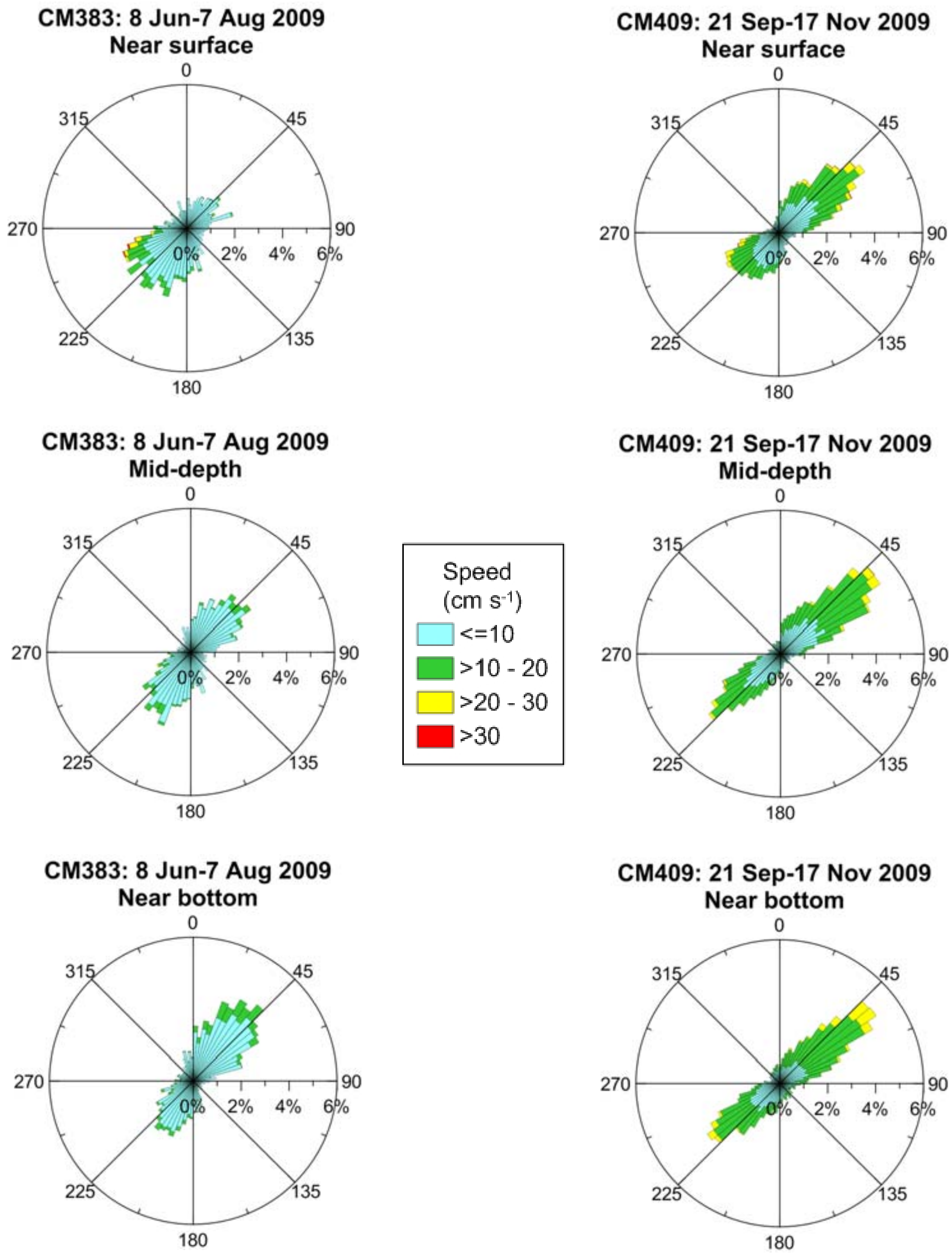


Fig. 18. Current velocity rose diagrams for two Acoustic Doppler Current Profiler current meter deployments at site D (see Fig. 16), near-surface, mid-depth, and near-bottom: CM383 (left column); CM409 (right column).

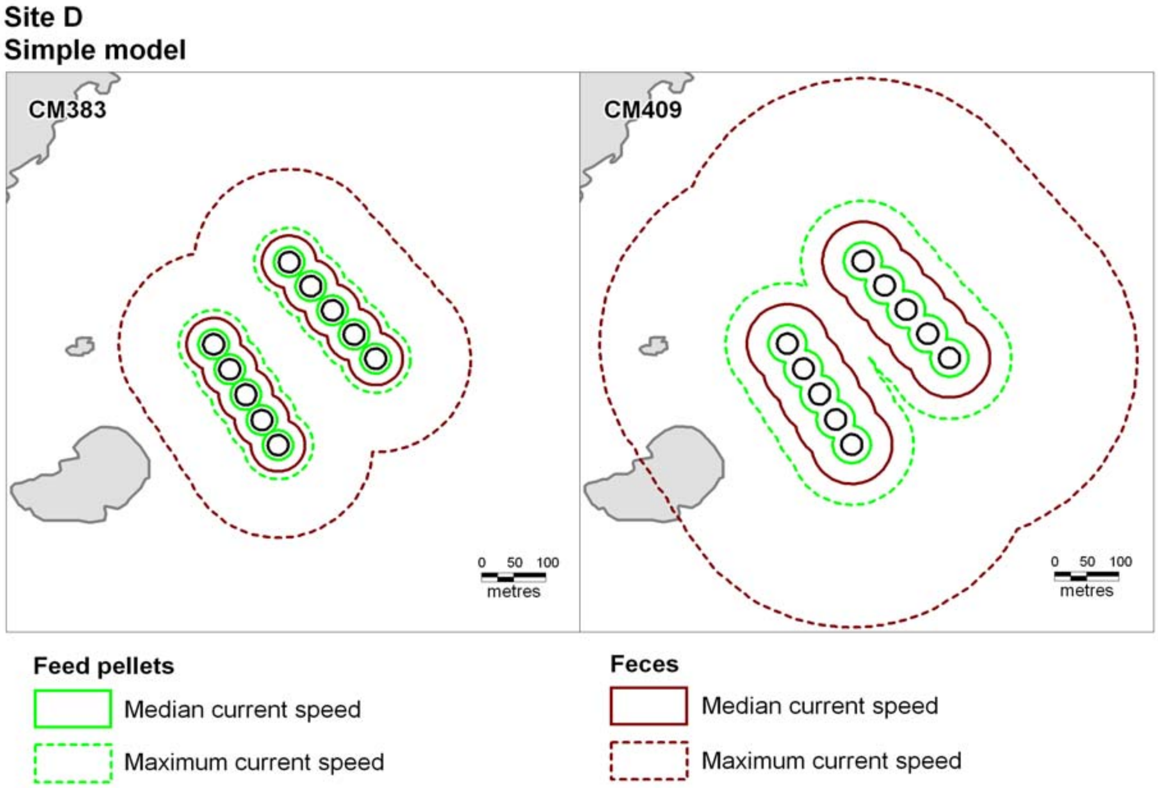


Fig. 19. Simple model estimates of area of seafloor impacted by feed pellets and feces released from cages at site D, using mid-depth current speeds from two current meter deployments near the farm: CM383 (left) and CM409 (right). The estimates assume mean sinking rates of 11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces. Black circles indicate approximate cage locations and sizes.

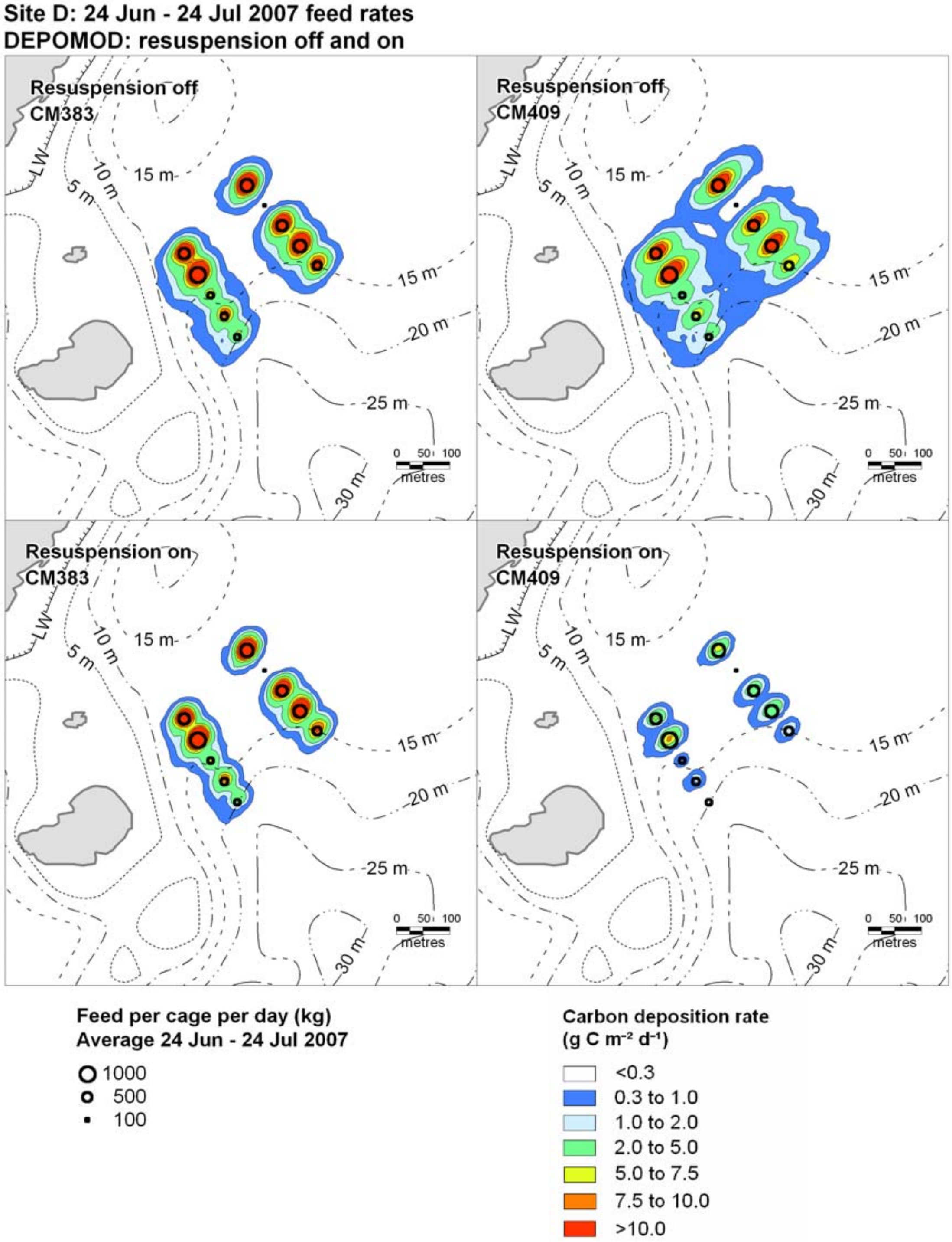


Fig. 20. Contour plots of DEPOMOD predicted carbon deposition rates at site D, resuspension off (top maps) and resuspension on (bottom maps). The model was run using two current meter deployments (CM383, left; CM409, right) and average daily feed rates during 24 June to 24 July 2007. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 24 June to 24 July 2007.

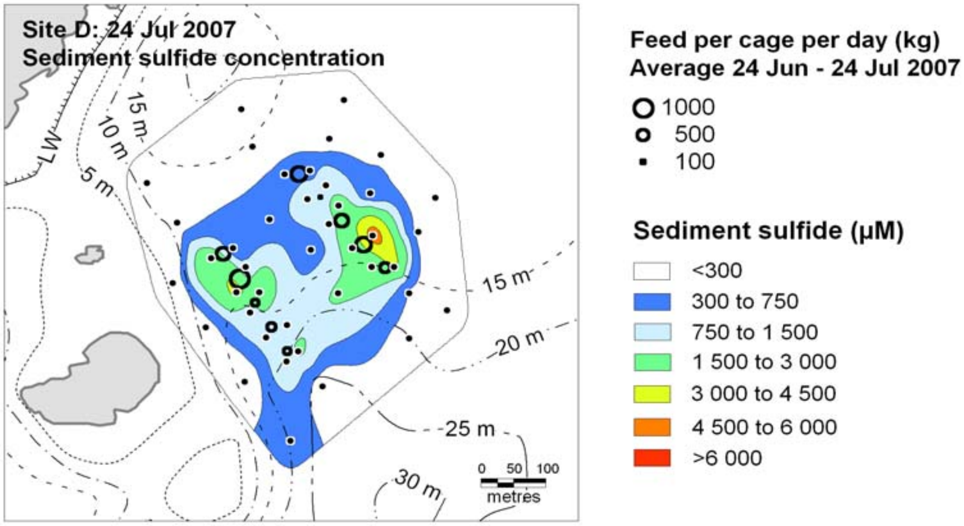


Fig. 21. Contour plots of sulfide levels at site D, derived from sediment grab samples taken on 24 July 2007. Triplicate sulfide measurements were taken from grab samples taken at 41 locations (black dots). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 24 June to 24 July 2007.

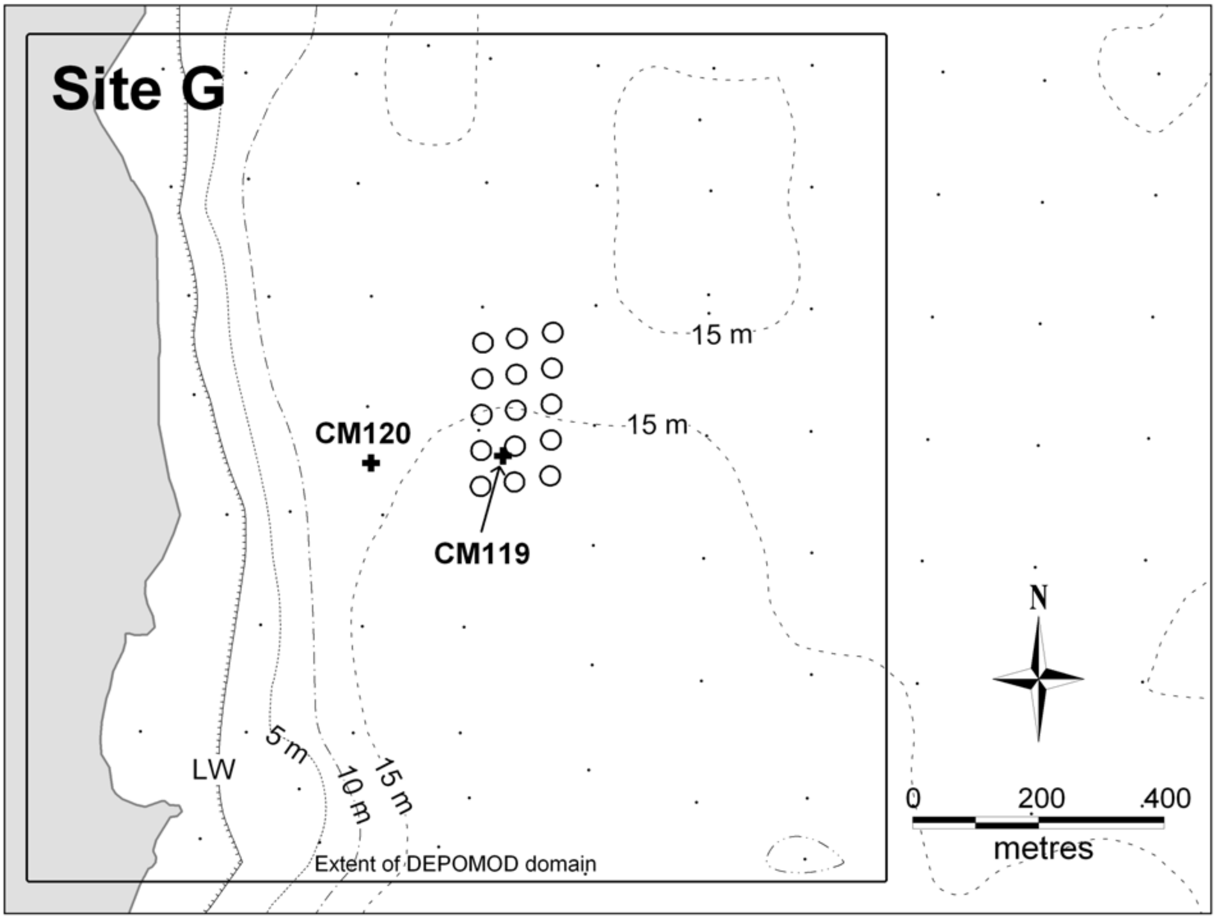


Fig. 22. Map of study site G, showing current meter locations (crosses), approximate cage locations and sizes (circles) at the time of sediment sampling, depth contours (relative to lowest normal tide, LW), and the extent of the DEPOMOD domain. The cage layout shown is at the time of Tier 2 monitoring in September 2010; the current meters were deployed in July-August 2001, when the cage layout was different (the cages in 2001 were located between the two current meter deployments). Dots indicate locations of CHS depth soundings.

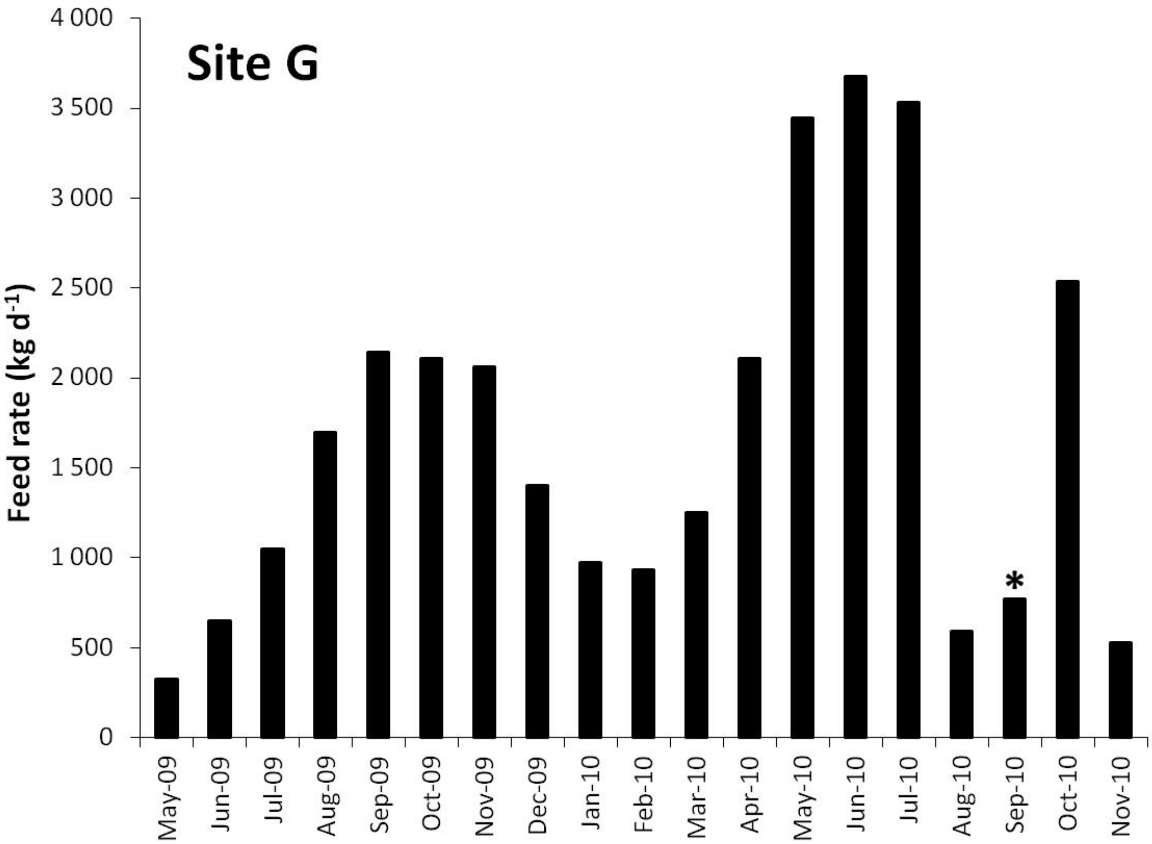


Fig. 23. Average daily feed rate per month at site G. The asterisk indicates the month when sediment sampling was conducted. Harvesting of this year-class was completed in July 2011.

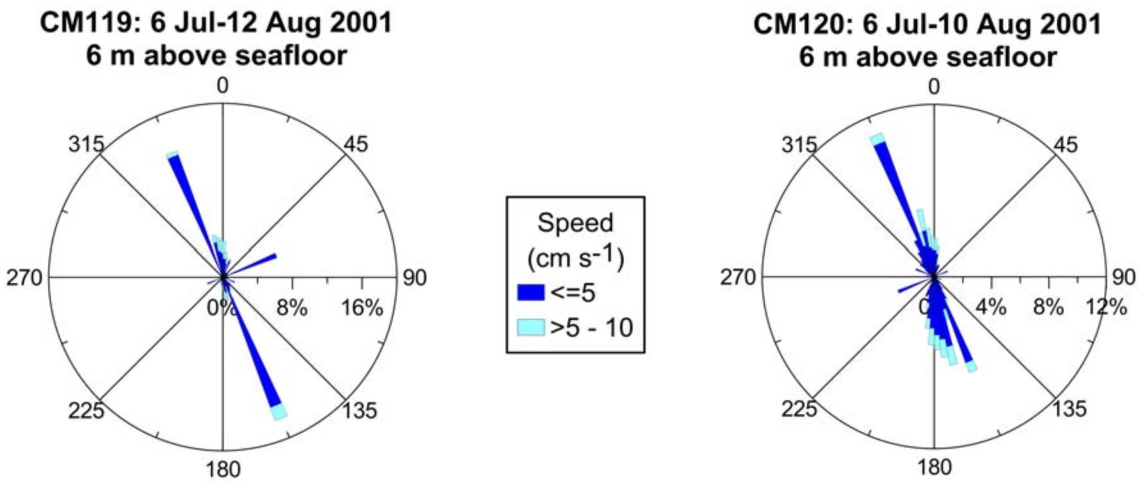


Fig. 24. Current velocity rose diagrams for two S4 current meter deployments at site G (see Fig. 22), 6 m above the seafloor: CM119 (left); CM120 (right).

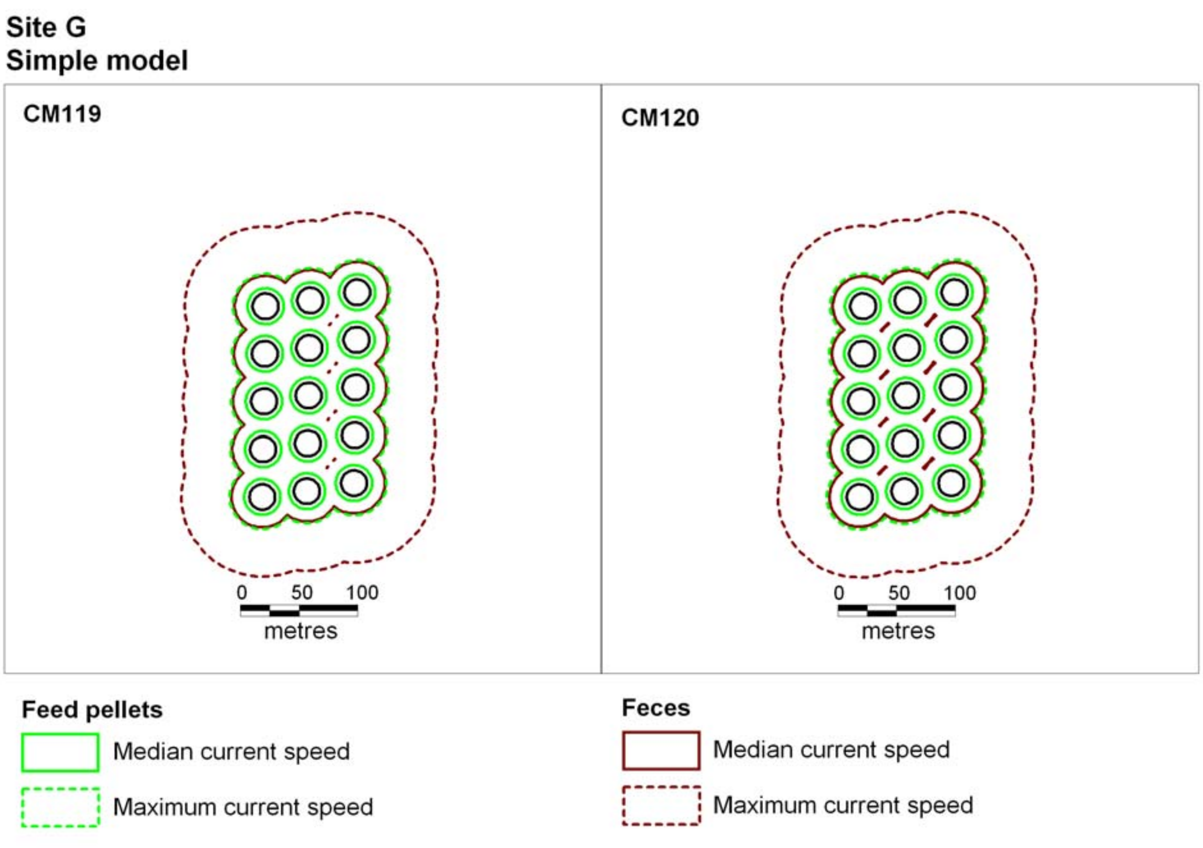


Fig. 25. Simple model estimates of area of seafloor impacted by feed pellets and feces released from cages at site G, using current speeds from two current meter deployments near the farm: CM119 (left) and CM120 (right). The estimates assume mean sinking rates of 11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces. Black circles indicate approximate cage locations and sizes.

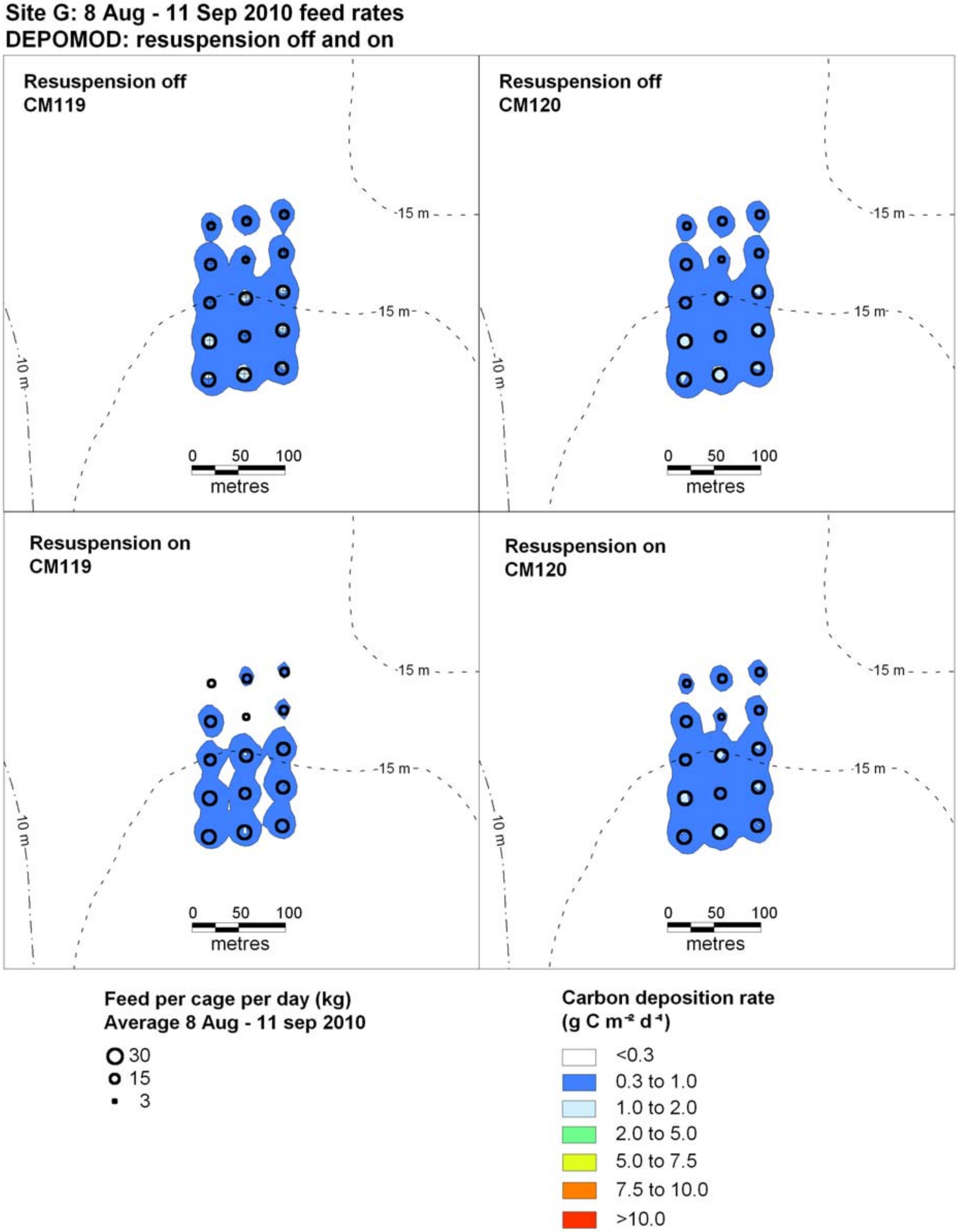


Fig. 26. Contour plots of DEPOMOD predicted carbon deposition rates at site G, resuspension off (top maps) and resuspension on (bottom maps). The model was run using two current meter deployments (CM119, left; CM120, right) and average daily feed rates during 8 August-11 September 2010. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 8 August-11 September 2010.

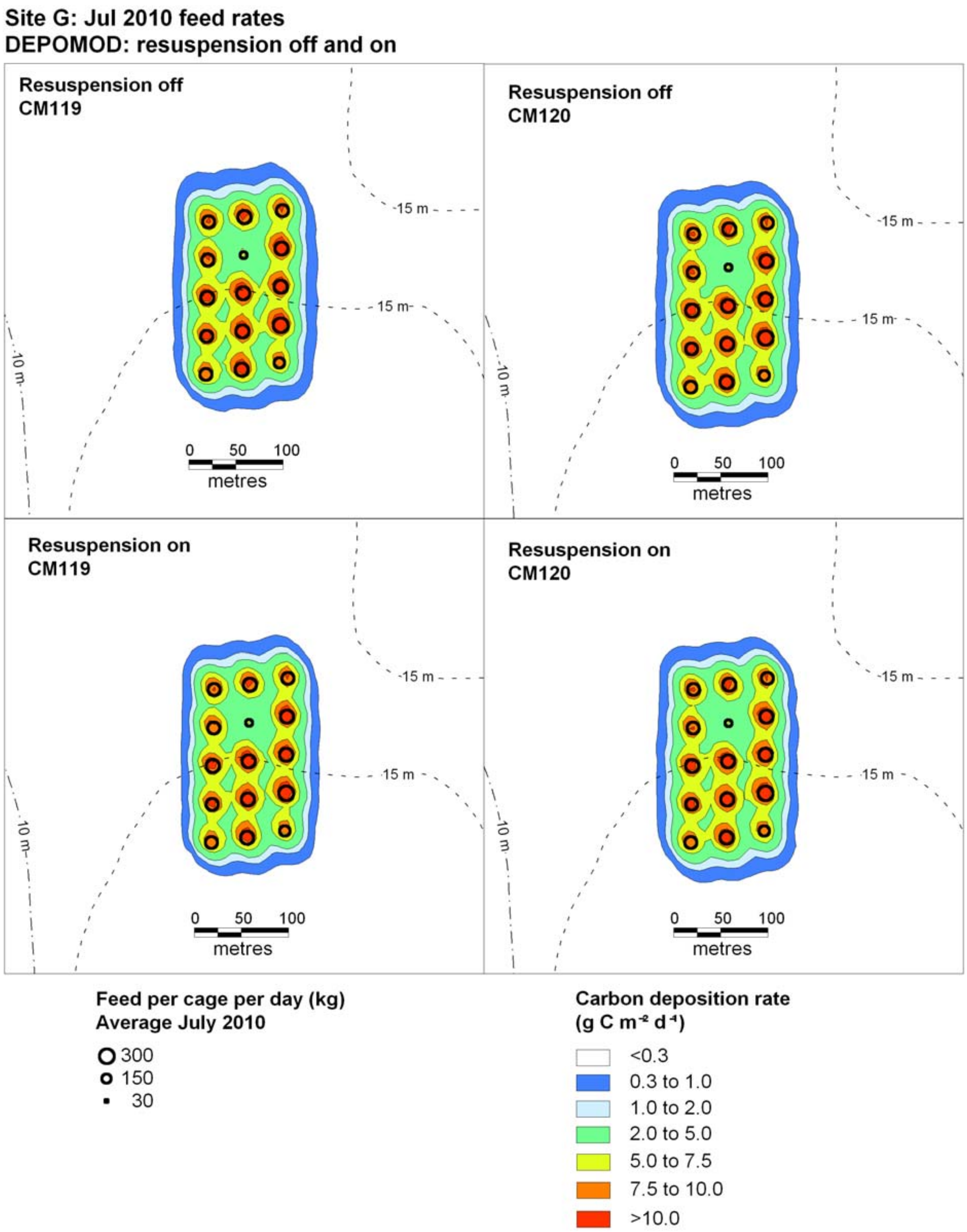


Fig. 27. Contour plots of DEPOMOD predicted carbon deposition rates at site G, resuspension off (top maps) and resuspension on (bottom maps). The model was run using two current meter deployments (CM119, left; CM120, right) and average daily feed rates during July 2010. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during July 2010.

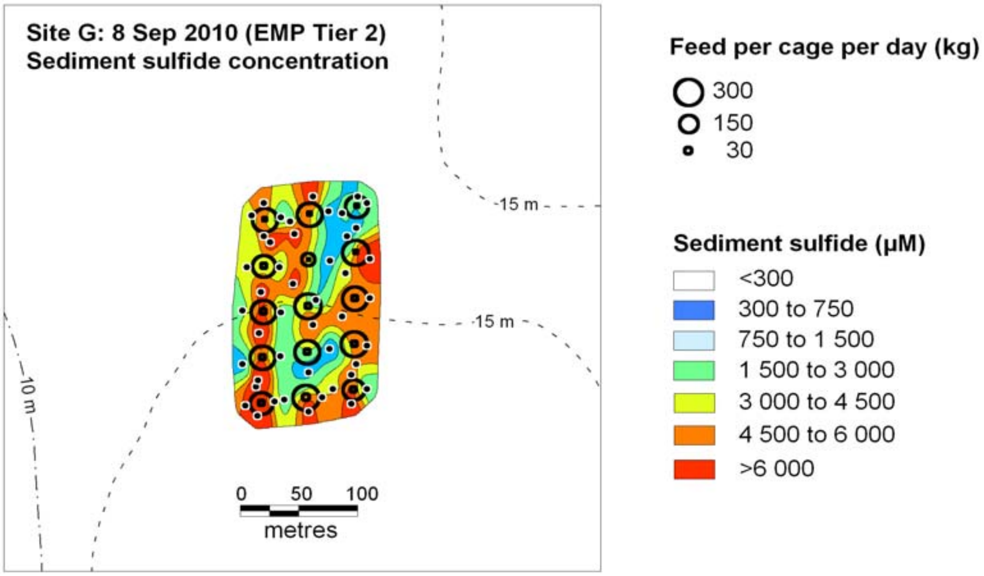


Fig. 28. Contour plots of sulfide levels at site G, derived from EMP Tier 2 sediment core samples taken on 8 September 2010. No samples were taken outside the cage array. One sulfide measurement was taken from each core sample (46 locations, indicated by black dots). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage: larger circles represent average daily feed rates during July 2010, and the smaller circles (inside the larger circles) represent the average daily feed rates during 8 August-11 September 2010.

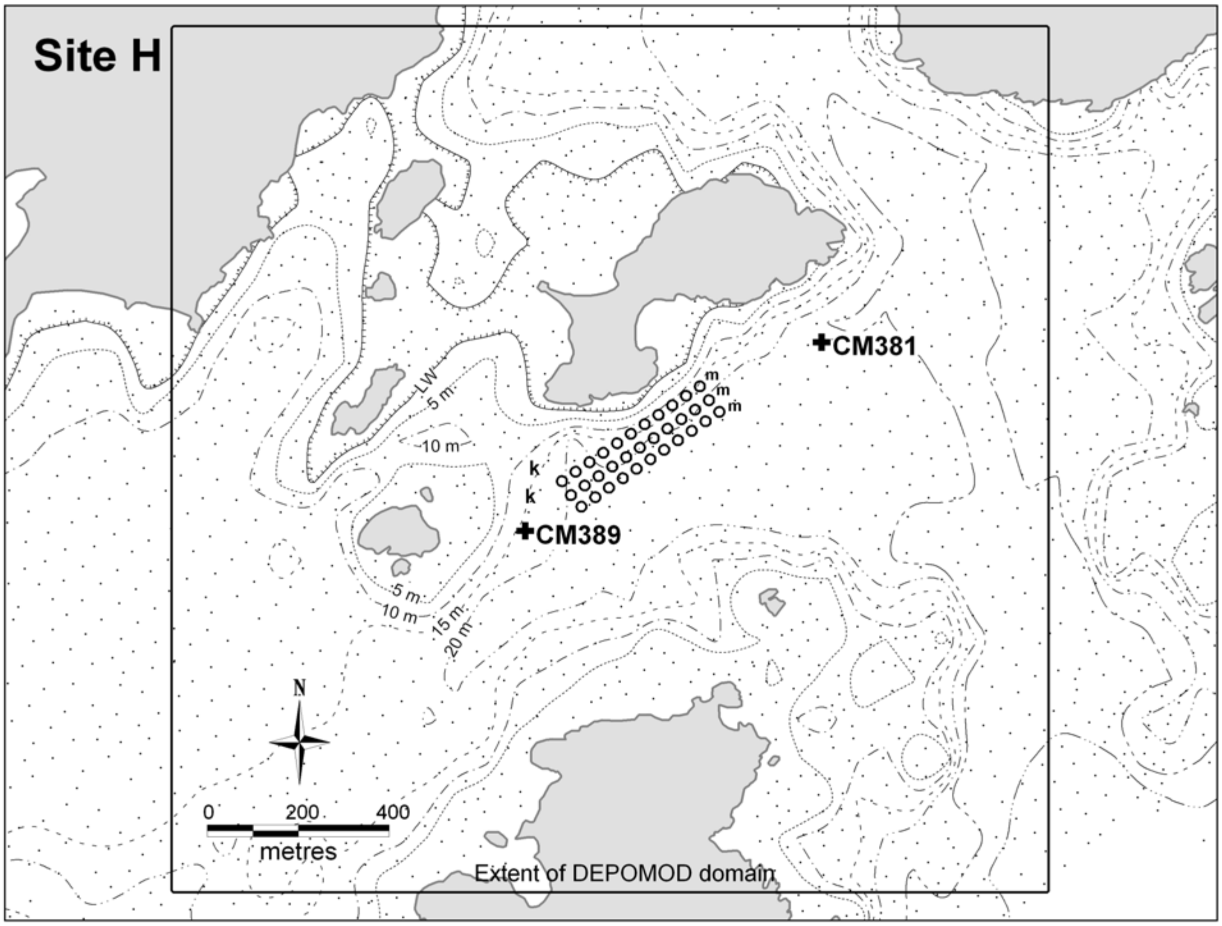


Fig. 29. Map of study site H, showing current meter locations (crosses), approximate cage locations and sizes (circles) at the time of sediment sampling, depth contours (relative to lowest normal tide, LW), and the extent of the DEPOMOD domain. Approximate locations of mussel (m) and kelp (k) rafts are also shown. Dots indicate locations of CHS depth soundings.

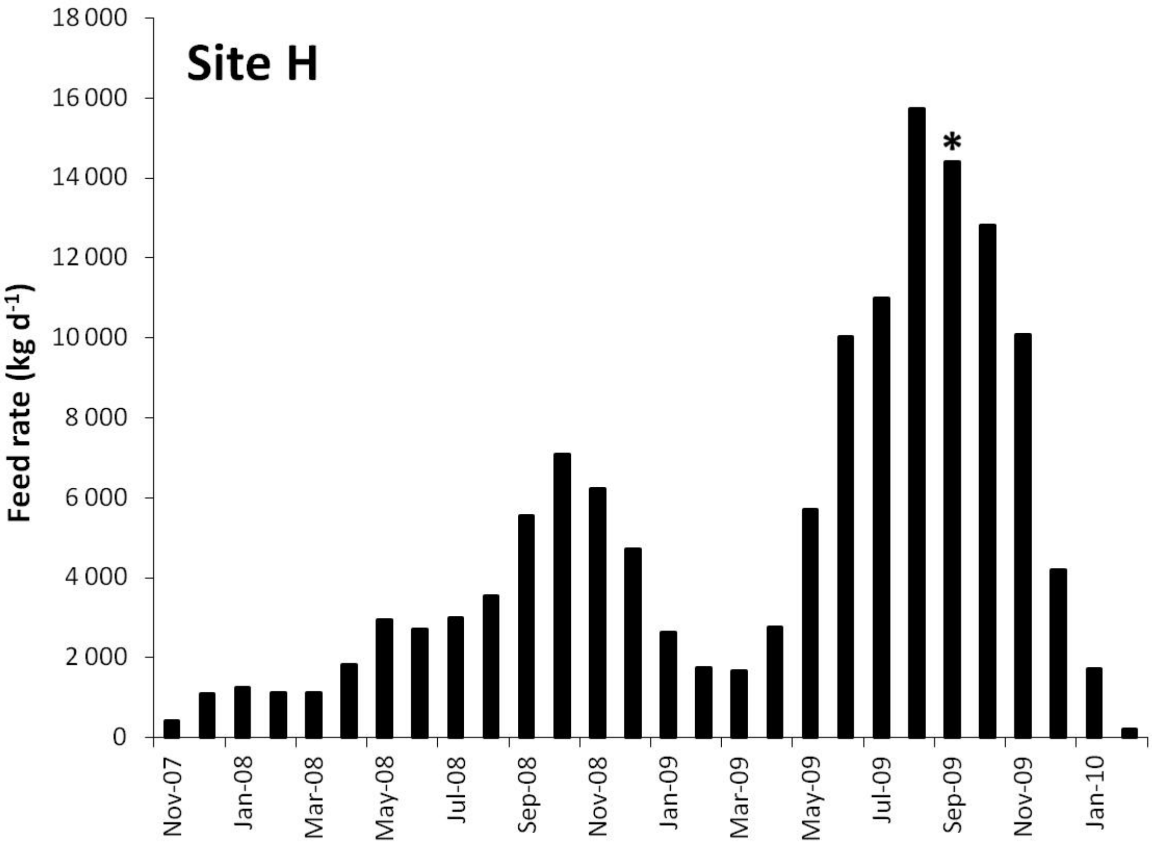


Fig. 30. Average daily feed rate per month at site H. The asterisk indicates the month when sediment sampling was conducted.

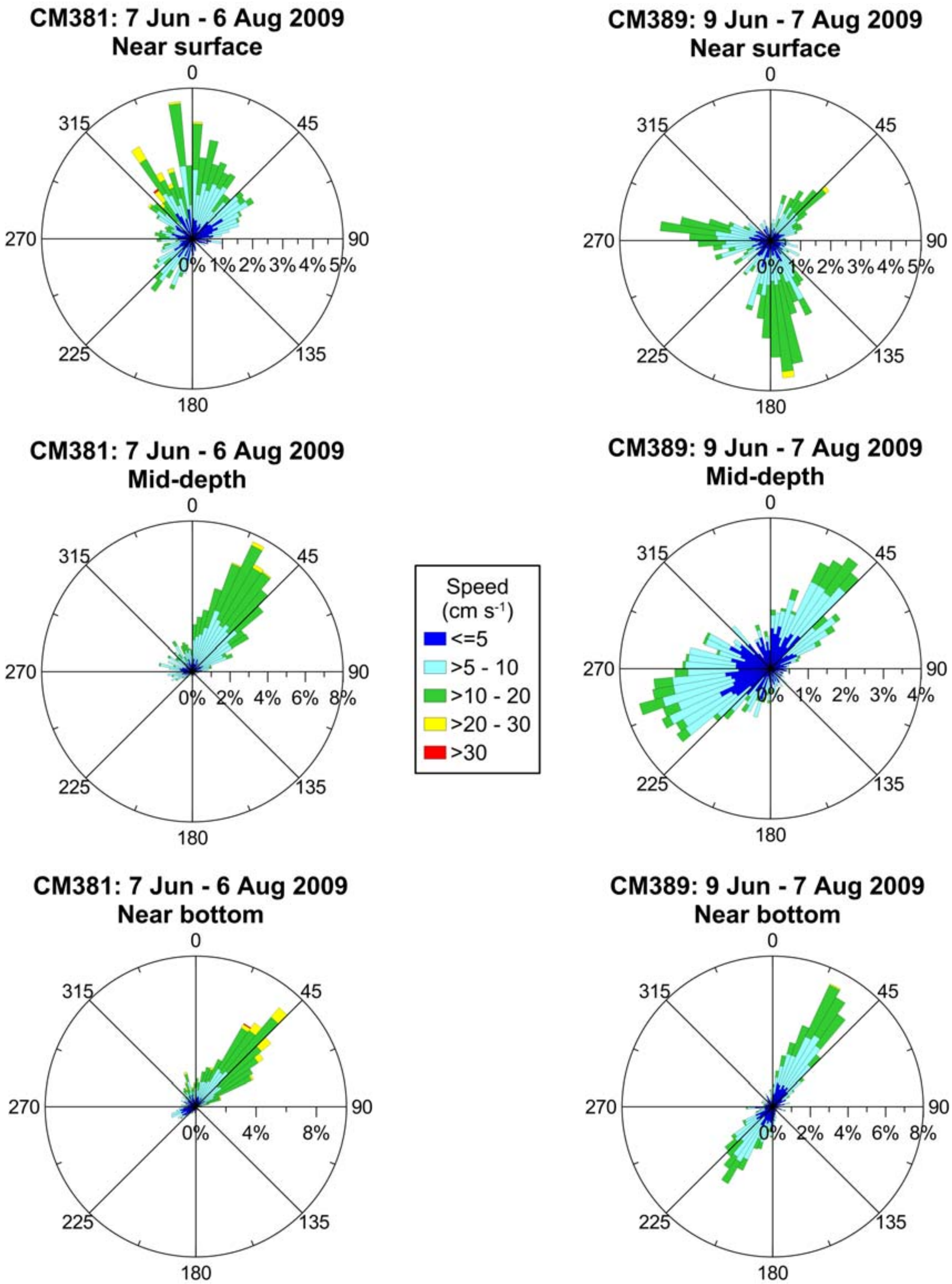


Fig. 31. Current velocity rose diagrams for two Acoustic Doppler Current Profiler current meter deployments at site H (see Fig. 29), near-surface, mid-depth, and near-bottom: CM381 (left column); CM389 (right column).

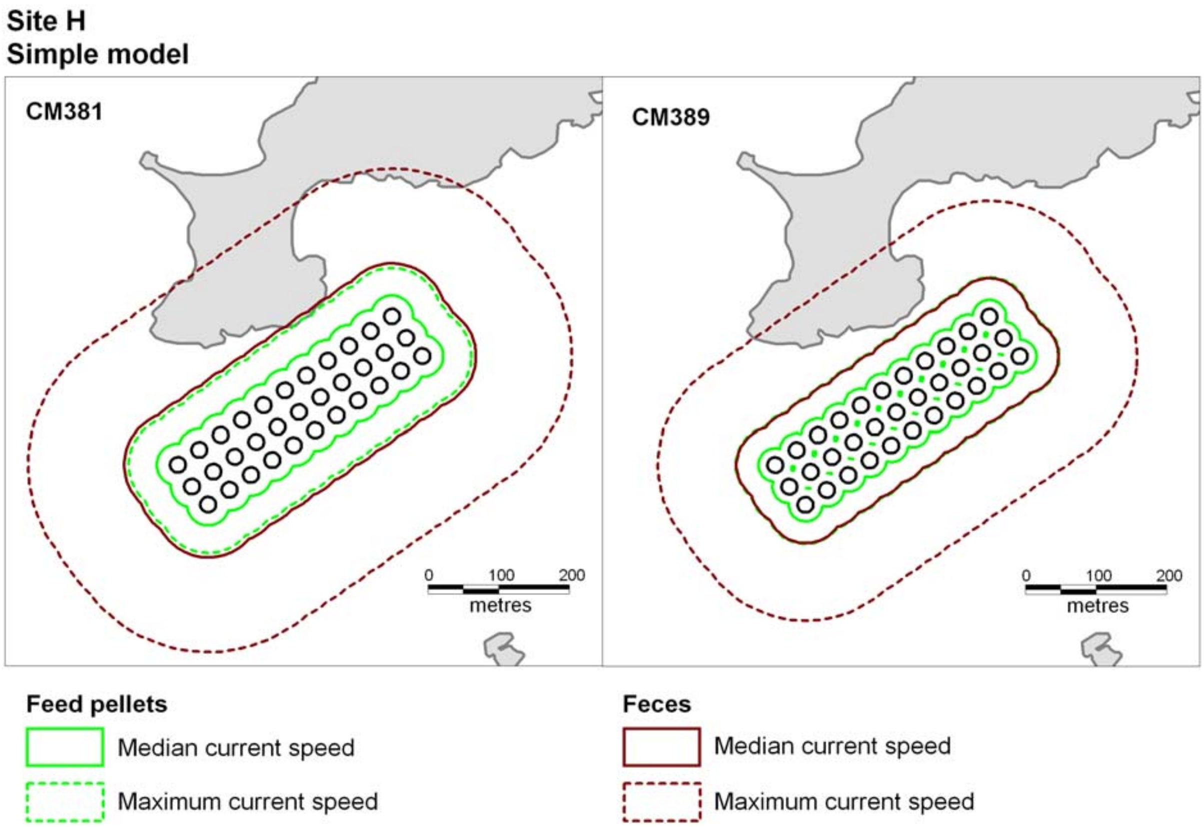


Fig. 32. Simple model estimates of area of seafloor impacted by feed pellets and feces released from cages at site H, using mid-depth current speeds from during two current meter deployments near the farm: CM381 (left) and CM389 (right). The estimates assume mean sinking rates of 11.0 cm s^{-1} for feed pellets and 3.2 cm s^{-1} for feces. Black circles indicate approximate cage locations and sizes

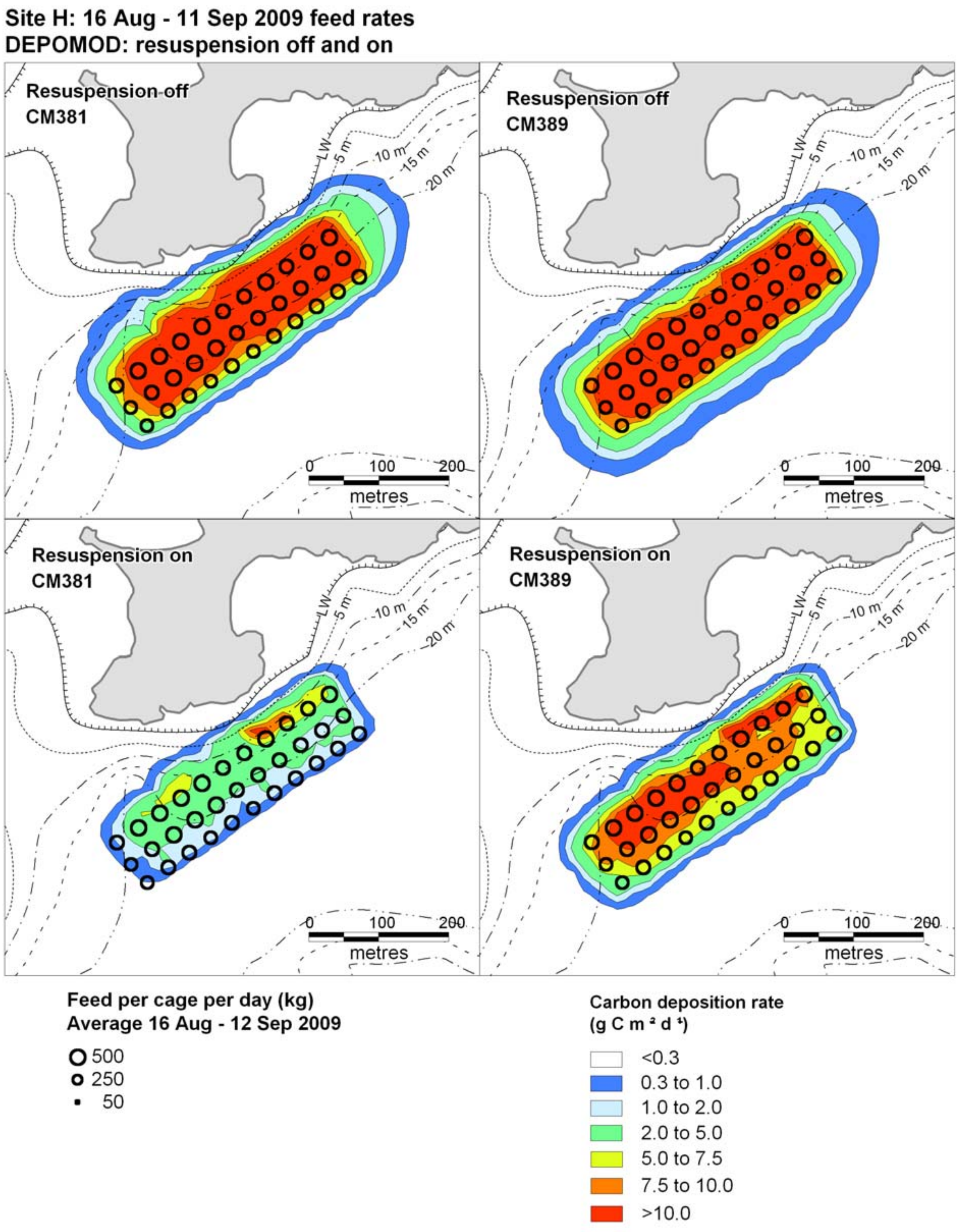


Fig. 33. Contour plots of DEPOMOD predicted carbon deposition rates at site H, resuspension off (top maps) and resuspension on (bottom maps). The model was run using two current meter deployments (CM381, left; CM389, right) and average daily feed rates during 16 August to 12 September 2009. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 16 August-12 September 2009.

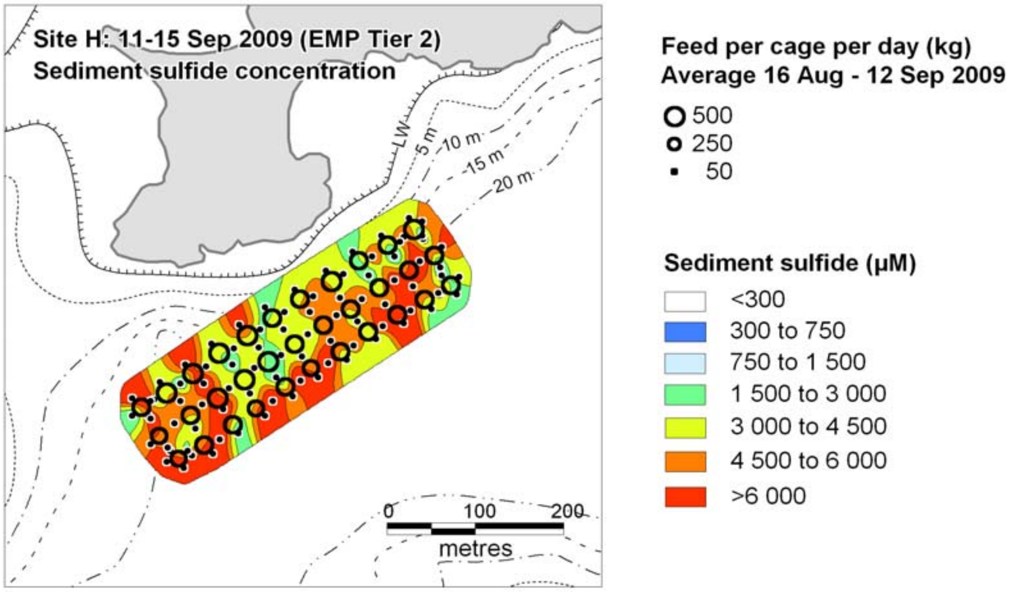
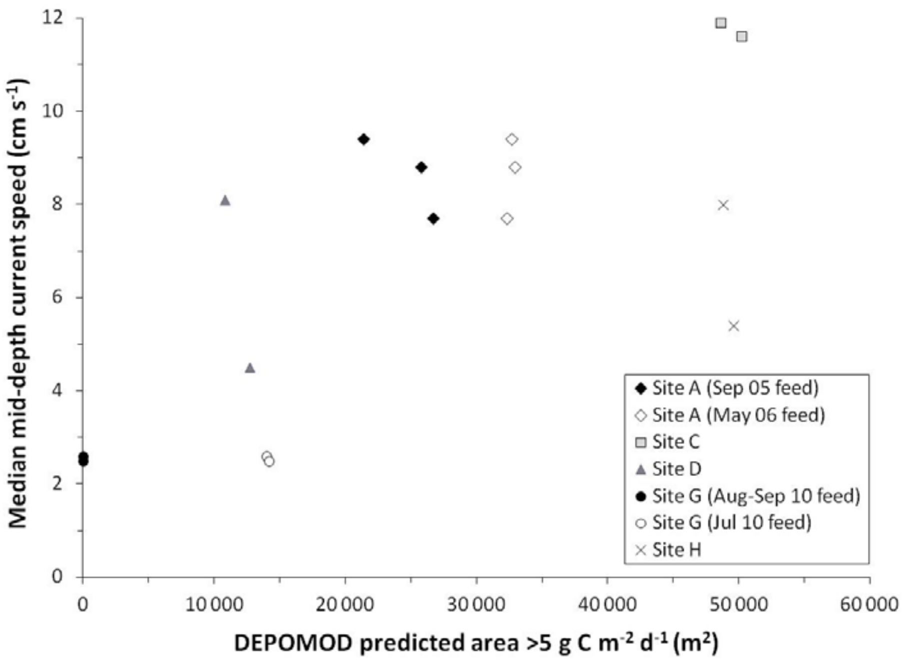


Fig. 34. Contour plots of sulfide levels at site H, derived from EMP Tier 2 sediment core samples taken on 11-15 September 2009. No samples were taken outside the cage array. One sulfide measurement was taken from each core sample (88 locations, indicated by black dots). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 16 August-12 September 2009.



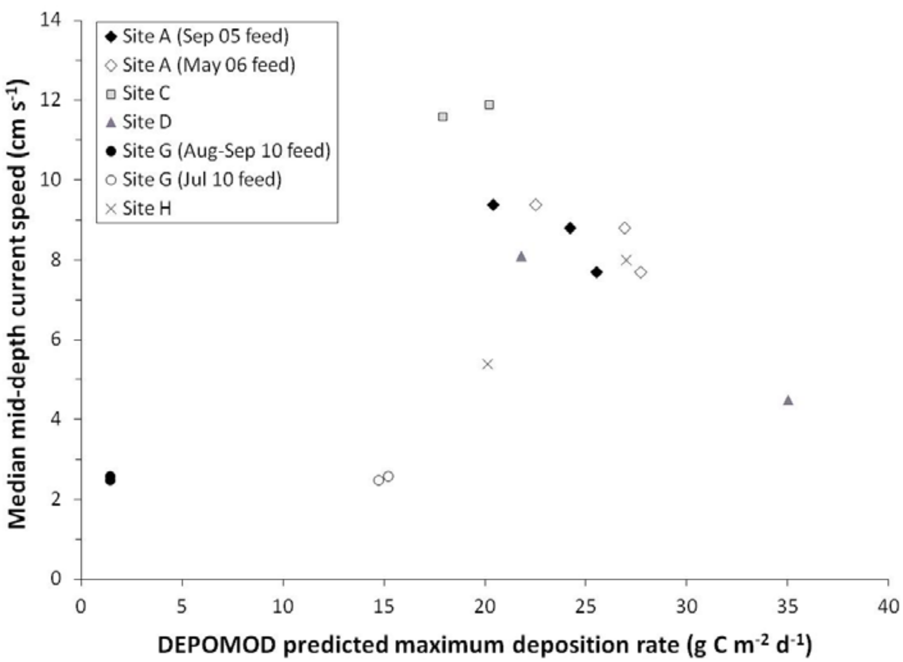


Fig. 35. Top: spatial extent of seafloor area with deposition rates >5 g C m^{-2} d^{-1} predicted by DEPOMOD (with resuspension off) versus median mid-depth current speed from current meter deployments at each site (two to three deployments per site). Bottom: maximum deposition rate predicted by DEPOMOD (with resuspension off) versus median mid-depth current speed from current meter deployments at each site (two to three deployments per site).

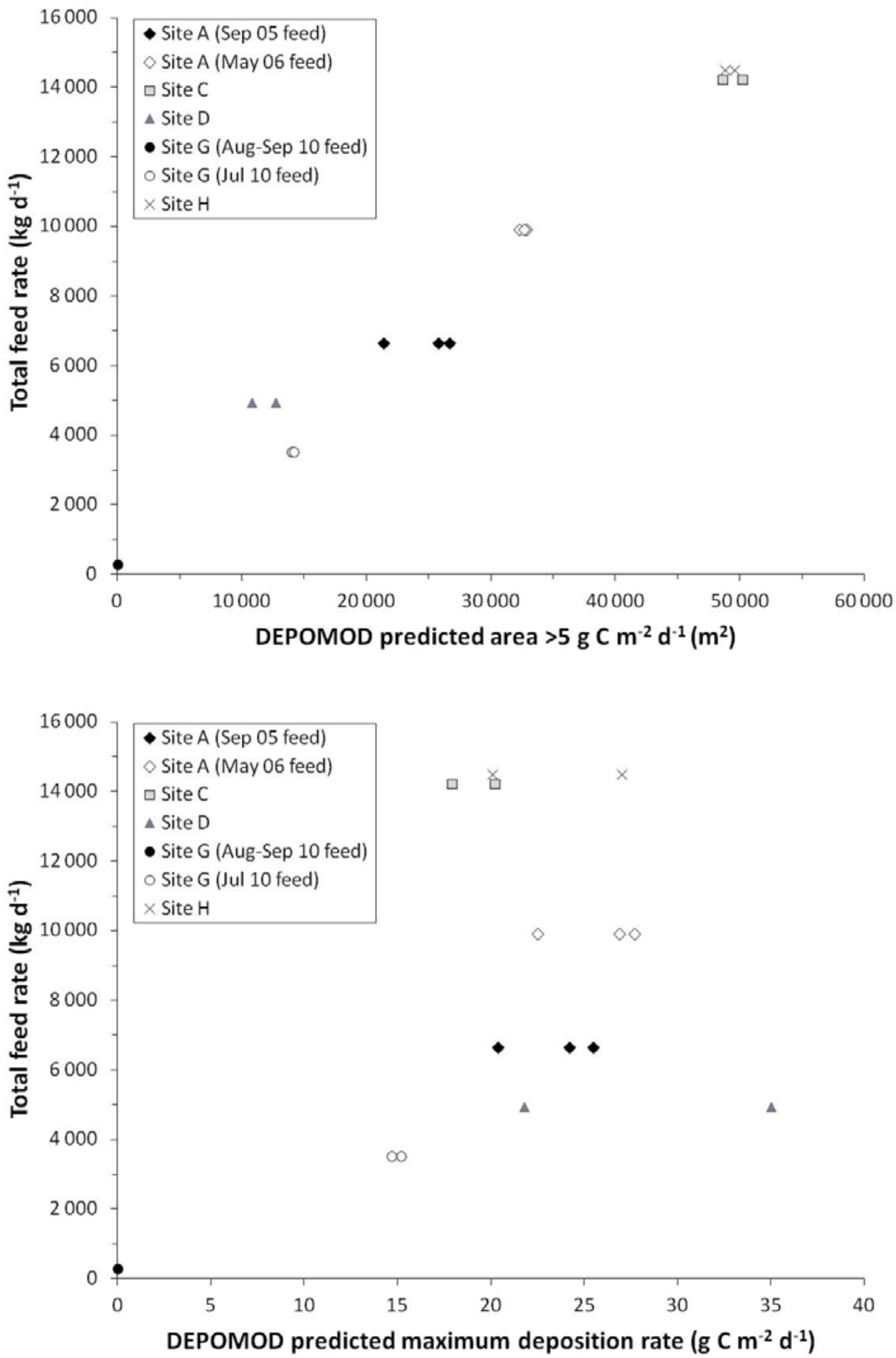


Fig. 36. Top: spatial extent of seafloor area with deposition rates >5 g C m^{-2} d^{-1} predicted by DEPOMOD (with resuspension off) versus total feed rate used in DEPOMOD at each site. Bottom: maximum deposition rate predicted by DEPOMOD (with resuspension off) versus total feed rate used in DEPOMOD at each site. DEPOMOD was run using current velocities from two to three current meter deployments per site.

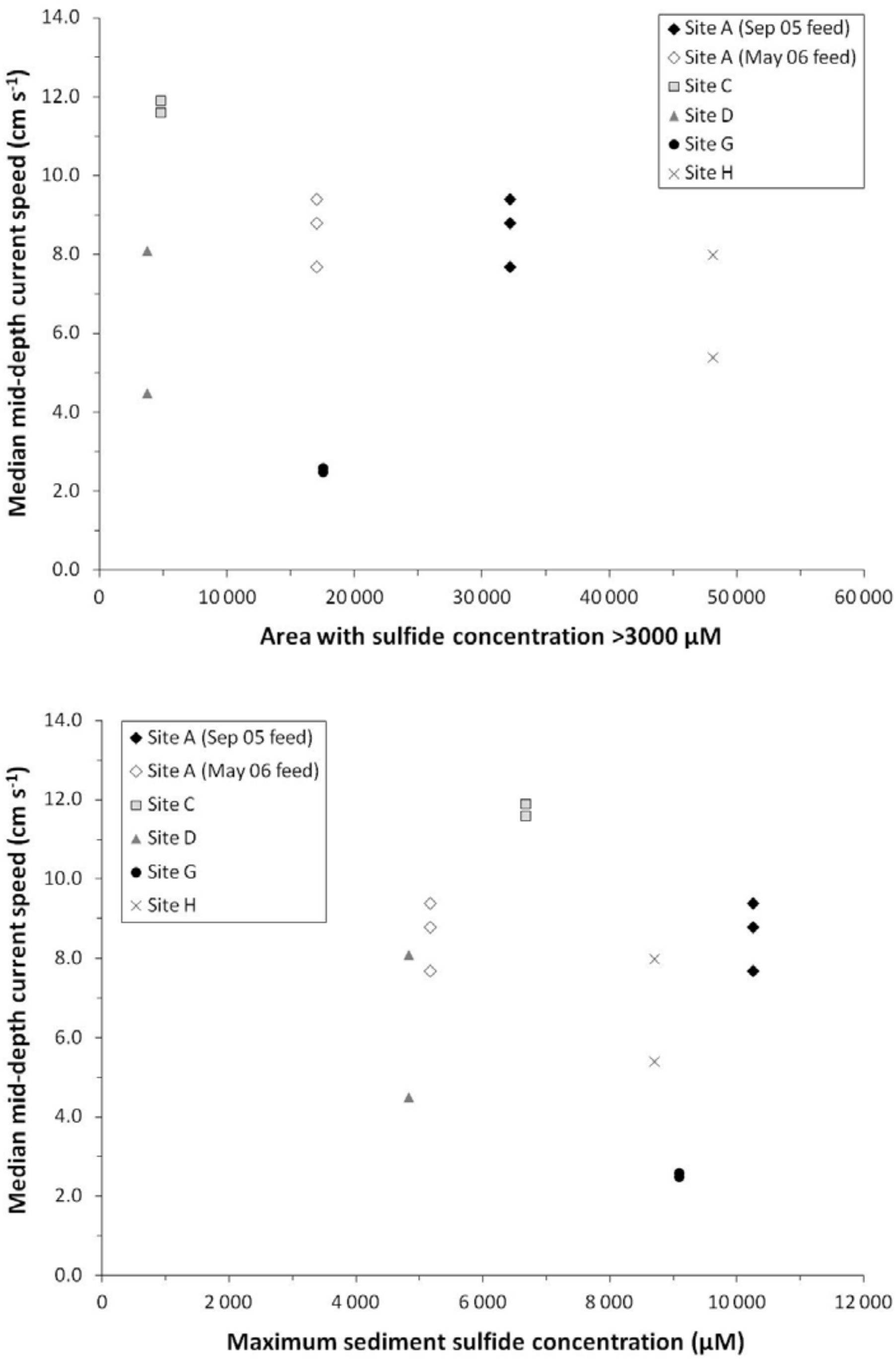


Fig. 37. Top: spatial extent of seafloor area with sediment sulfide concentration >3,000 µM versus median mid-depth current speed from current meter deployments at each site (two to three deployments per site). Bottom: maximum sediment sulfide concentration versus median mid-depth current speed from current meter deployments at each site (two to three deployments per site).

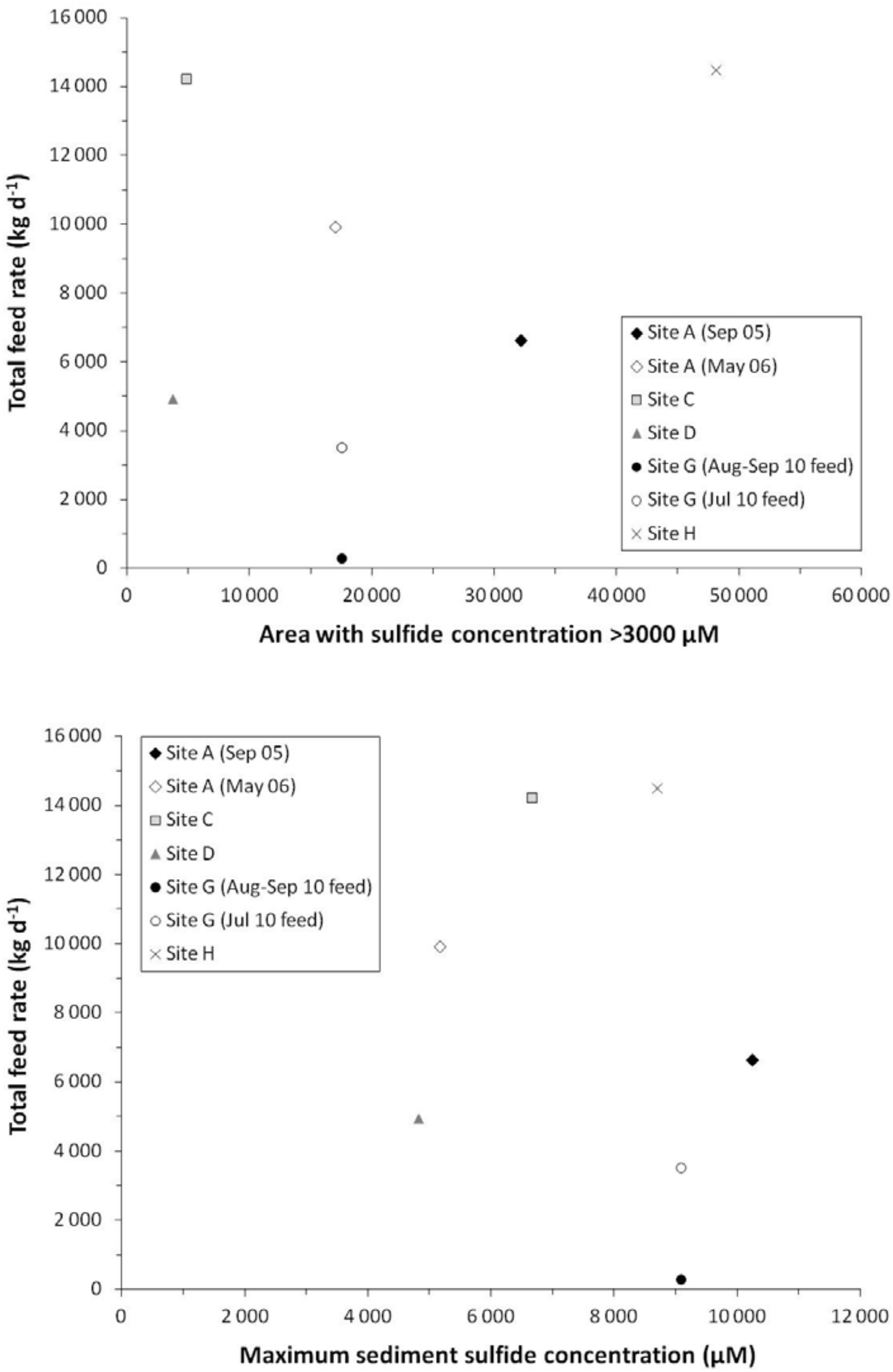


Fig. 38. Top: spatial extent of seafloor area with sediment sulfide concentration >3,000 µM versus total feed rate at each site. Bottom: maximum sediment sulfide concentration versus total feed rate at each site. Feed rates are at the time of sediment sampling, except for site G (Jul 10 feed), which uses a higher feed rate from earlier in the summer.

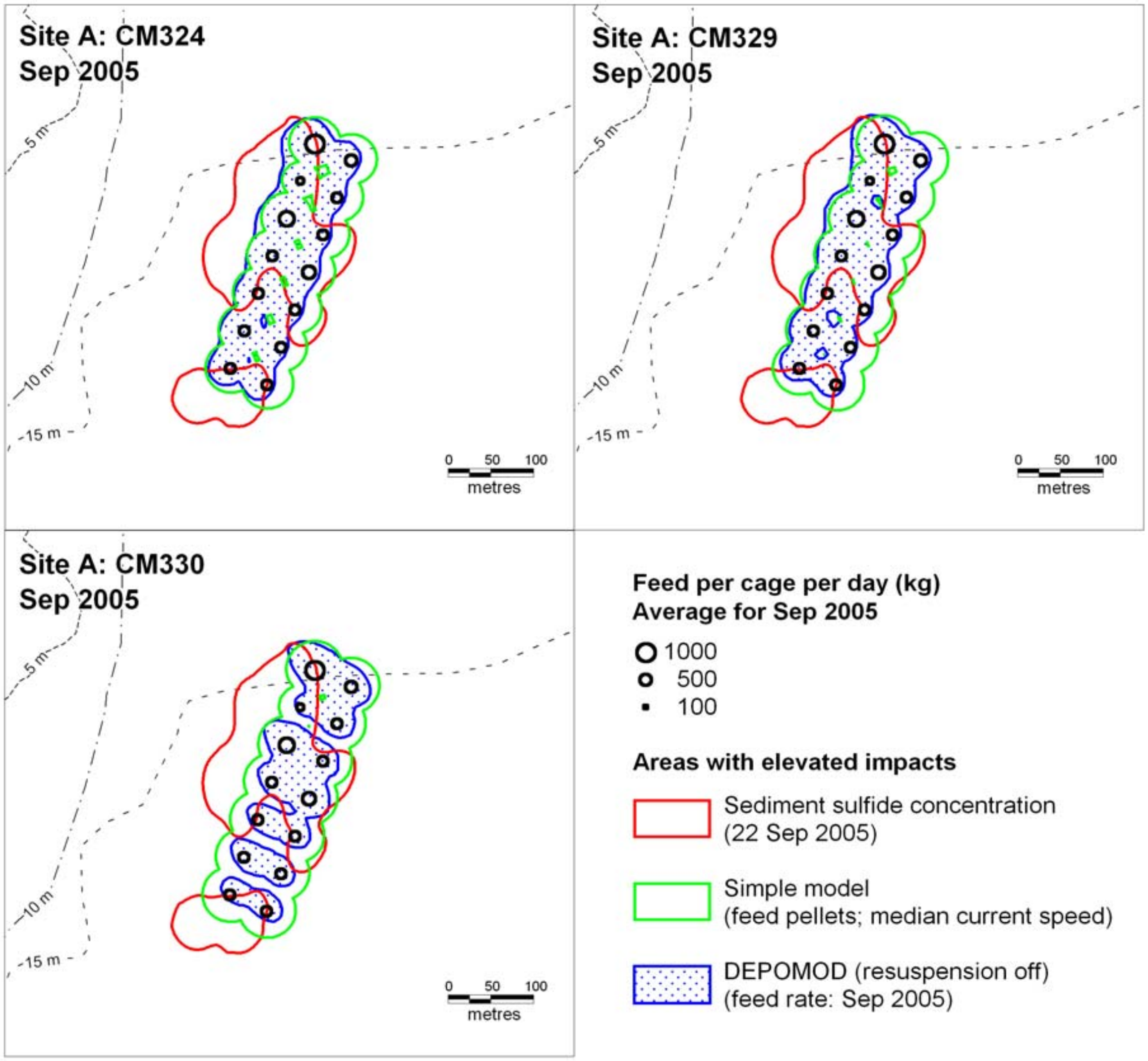


Fig. 39. Comparisons of areas of elevated benthic impacts at site A measured in sediment samples (sulfide concentration >3,000 µM on 22 September 2005) with predictions using a simple model (predicted displacement of feed pellets at median current speeds) and DEPOMOD (predicted deposition rate >5 g C m^{-2} d^{-1}, with resuspension off). The models were run using current velocity data from three current meter deployments. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005.

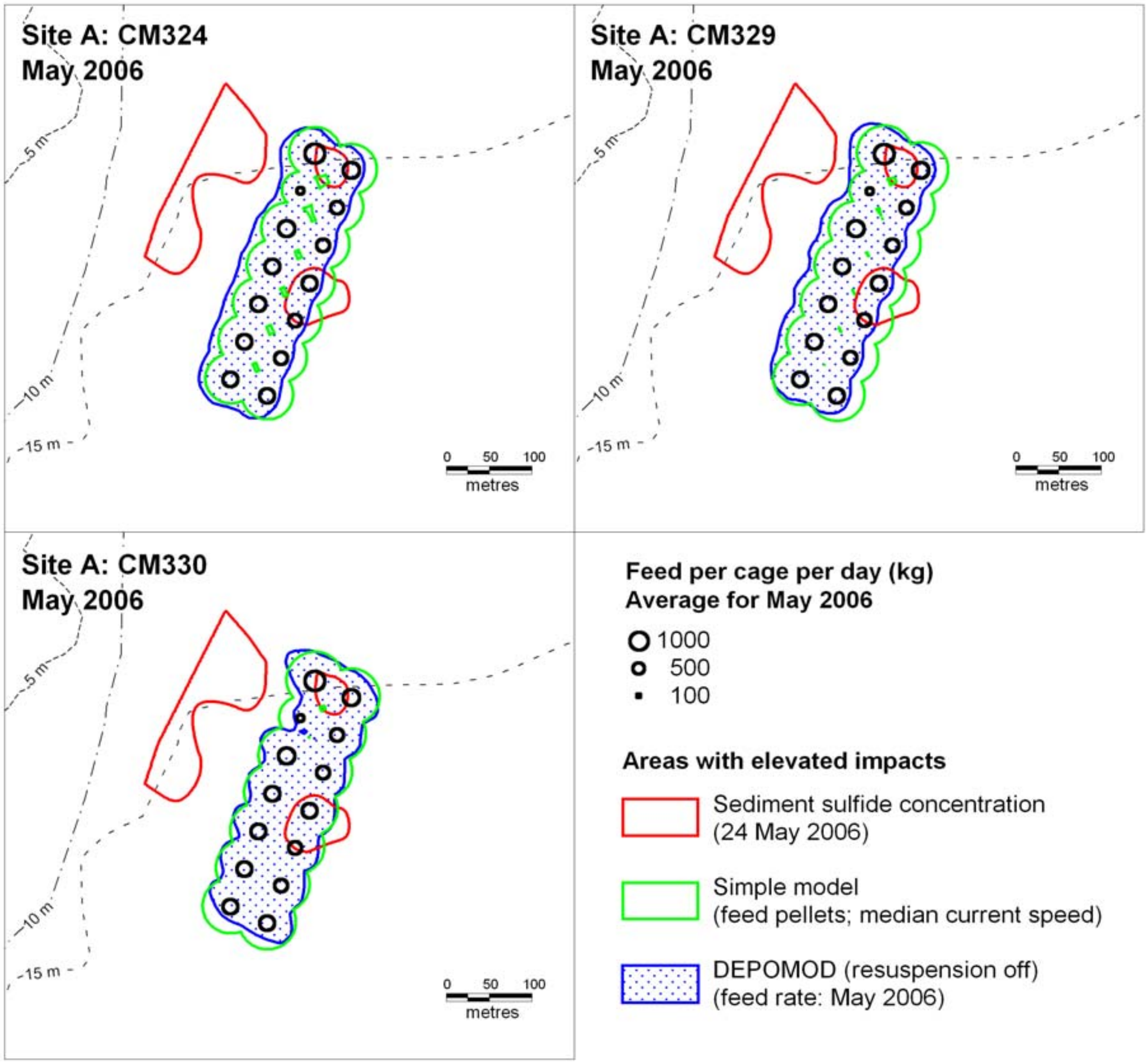


Fig. 40. Comparisons of areas of elevated benthic impacts at site A measured in sediment samples (sulfide concentration >3,000 µM on 24 May 2006) with predictions using a simple model (predicted displacement of feed pellets at median current speeds) and DEPOMOD (predicted deposition rate >5 g C m^{-2} d^{-1}, with resuspension off). The models were run using current velocity data from three current meter deployments. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during May 2006.

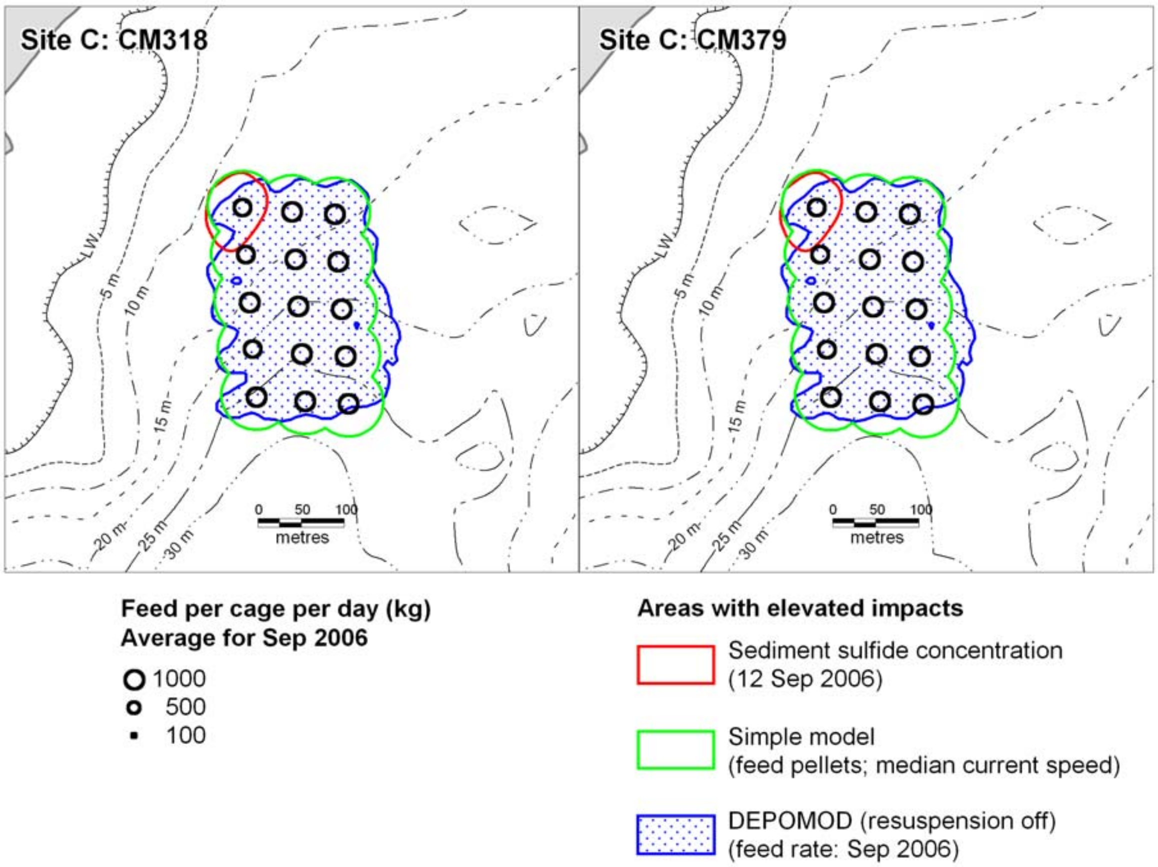


Fig. 41. Comparisons of areas of elevated benthic impacts at site C measured in sediment samples (sulfide concentration >3,000 µM on 12 September 2006) with predictions using a simple model (predicted displacement of feed pellets at median current speeds) and DEPOMOD (predicted deposition rate >5 g C m^{-2} d^{-1}, with resuspension off). The models were run using current velocity data from two current meter deployments. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2006.

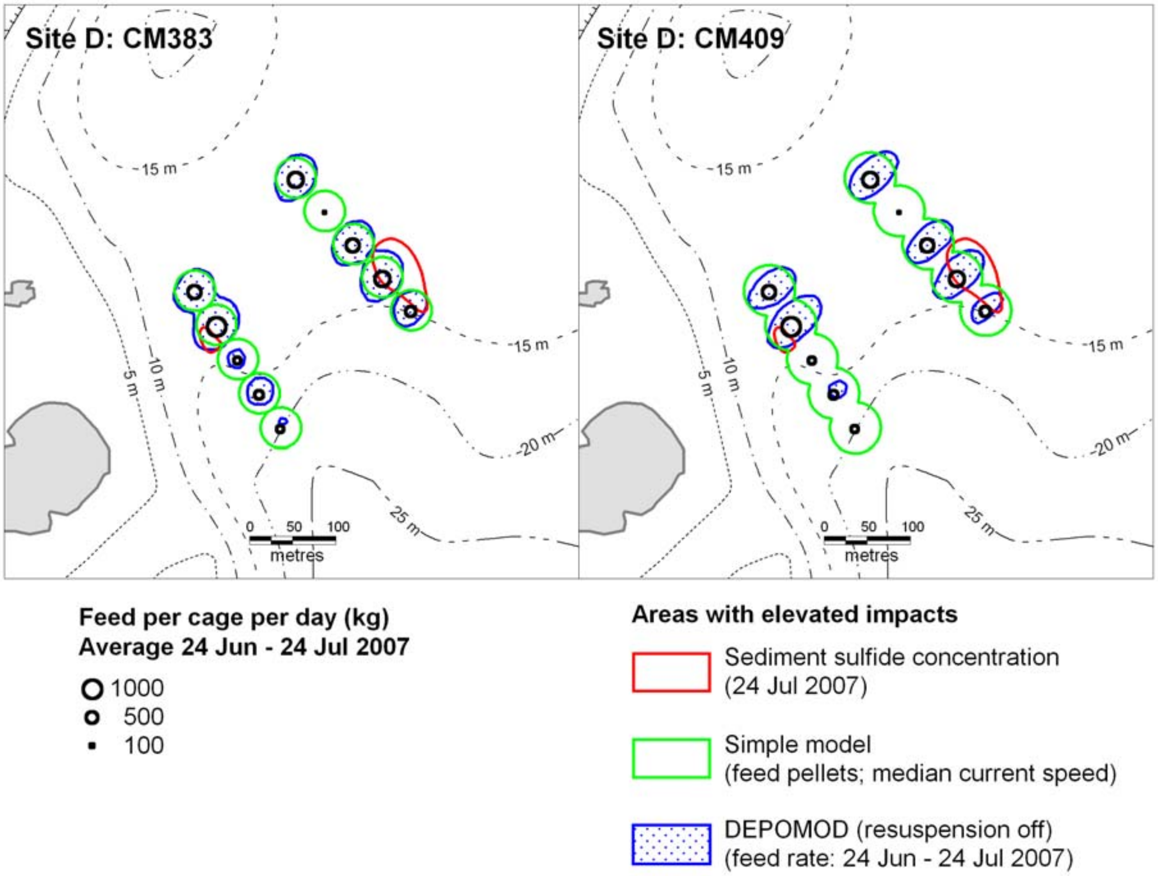


Fig. 42. Comparisons of areas of elevated benthic impacts at site D measured in sediment samples (sulfide concentration >3,000 μM on 24 July 2007) with predictions using a simple model (predicted displacement of feed pellets at median current speeds) and DEPOMOD (predicted deposition rate >5 g C m^{-2} d^{-1}, with resuspension off). The models were run using current velocity data from two current meter deployments. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 24 June to 24 July 2007.

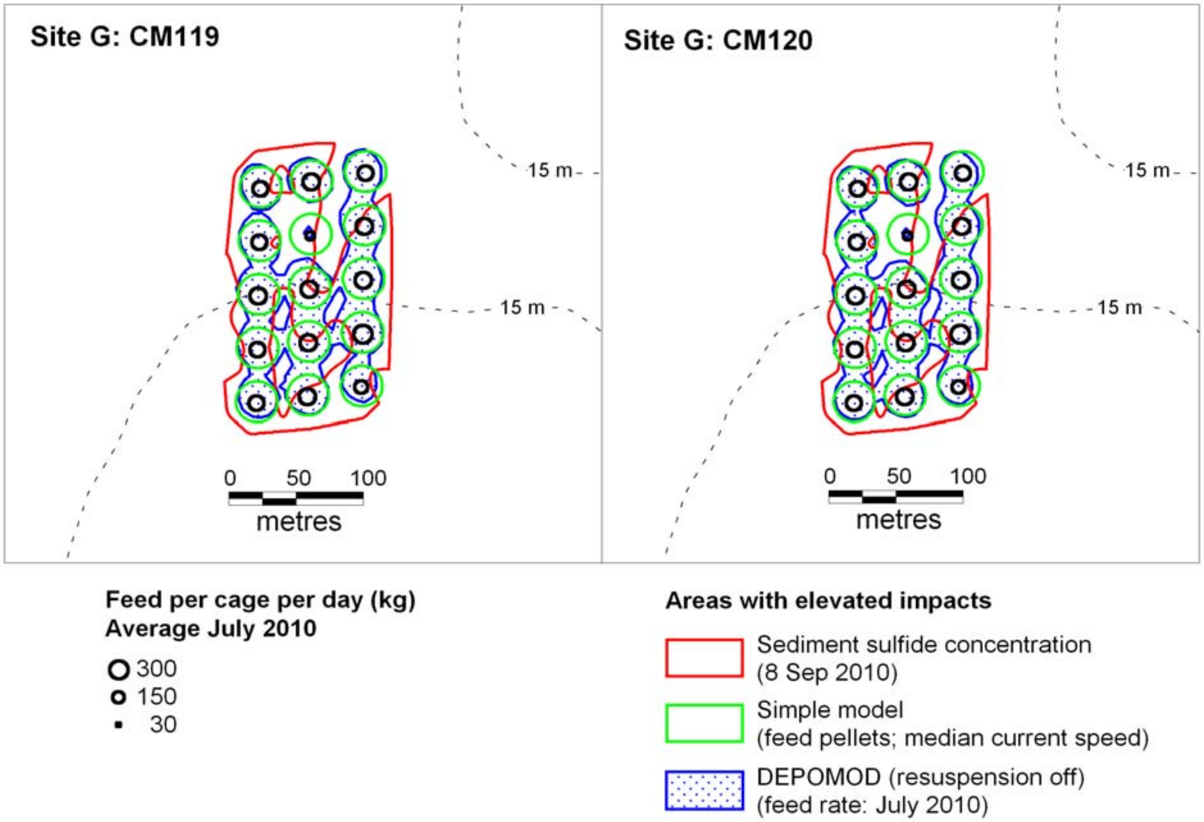


Fig. 43. Comparisons of areas of elevated benthic impacts at site G measured in sediment samples (sulfide concentration >3,000 µM on 8 September 2010) with predictions using a simple model (predicted displacement of feed pellets at median current speeds) and DEPOMOD (predicted deposition rate >5 g C m^{-2} d^{-1} using feed rates for July 2010, with resuspension off). The models were run using current velocity data from two current meter deployments. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during July 2010. When DEPOMOD was run using feed rates for the period leading up to the sediment sampling date (8 August – 11 September 2011), there were no areas where the predicted deposition rate was >5 g C m^{-2} d^{-1}.

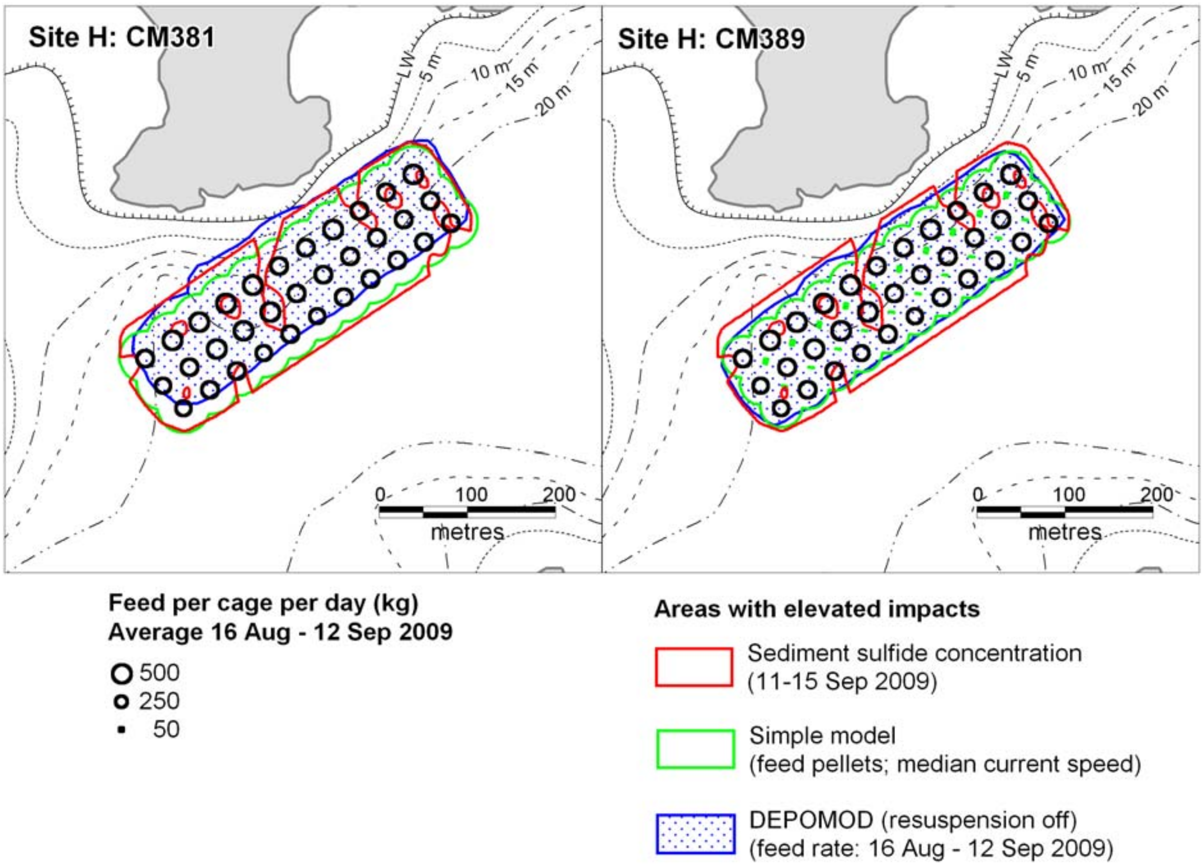


Fig. 44. Comparisons of areas of elevated benthic impacts at site H measured in sediment samples (sulfide concentration >3,000 µM on 11-15 September 2009) with predictions using a simple model (predicted displacement of feed pellets at median current speeds) and DEPOMOD (predicted deposition rate >5 g C m^{-2} d^{-1}, with resuspension off). The models were run using current velocity data from two current meter deployments. Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 16 August-12 September 2009.

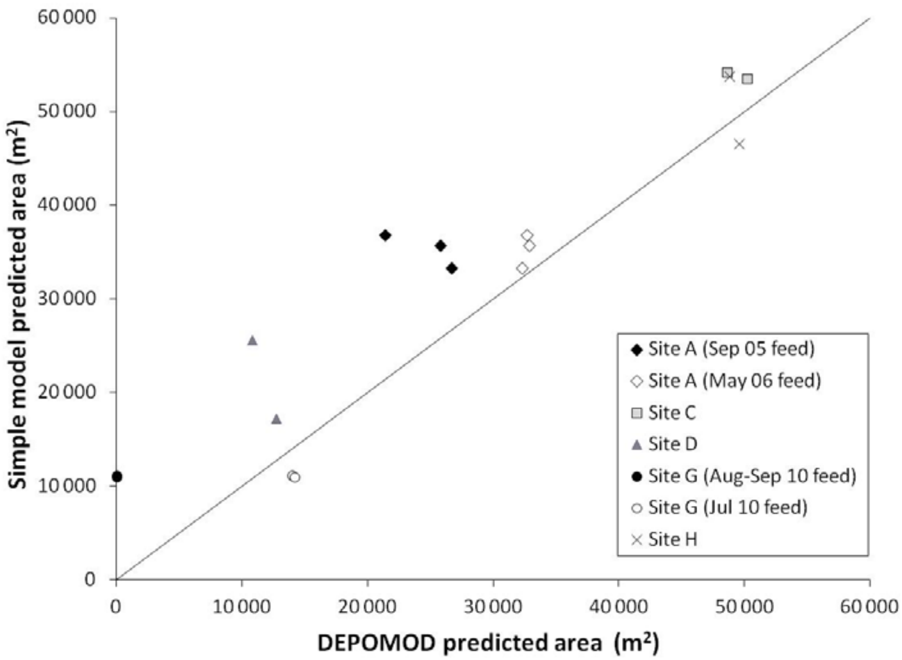


Fig. 45. Relationship among study sites between the spatial extent of seafloor area with elevated impacts predicted by DEPOMOD (seafloor area with deposition rate >5 g C m^{-2} d^{-1}) and the spatial extent of impacted seafloor area predicted by a simple model (based on displacement of feed particles at median current speeds). The line represents a 1:1 relationship.

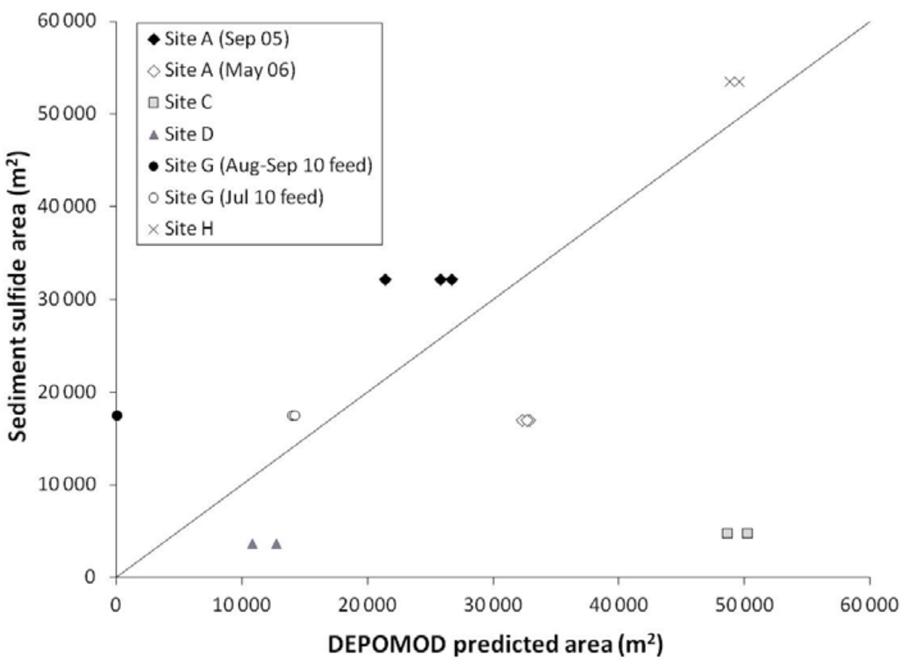


Fig. 46. Relationship among study sites between the spatial extent of seafloor area with elevated impacts predicted by DEPOMOD (seafloor area with deposition rate >5 g C m^{-2} d^{-1}) and the seafloor area with elevated sediment sulfide concentration (>3,000 µM). The line represents a 1:1 relationship.

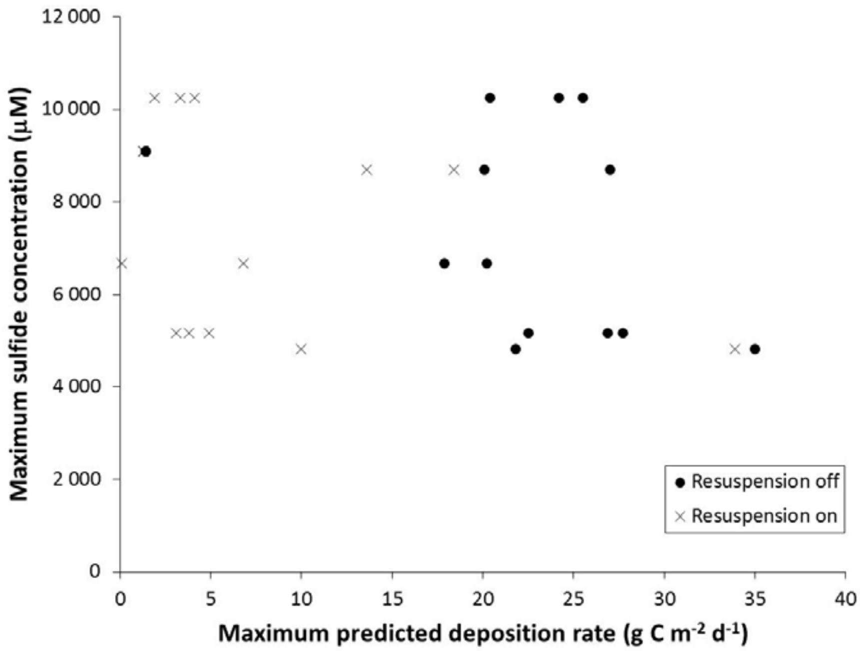
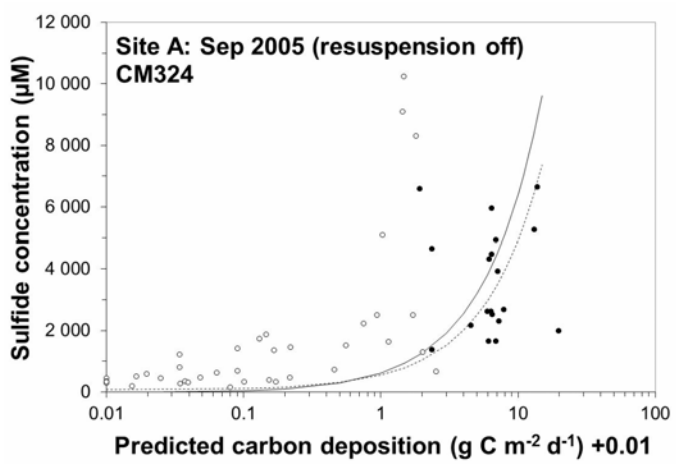
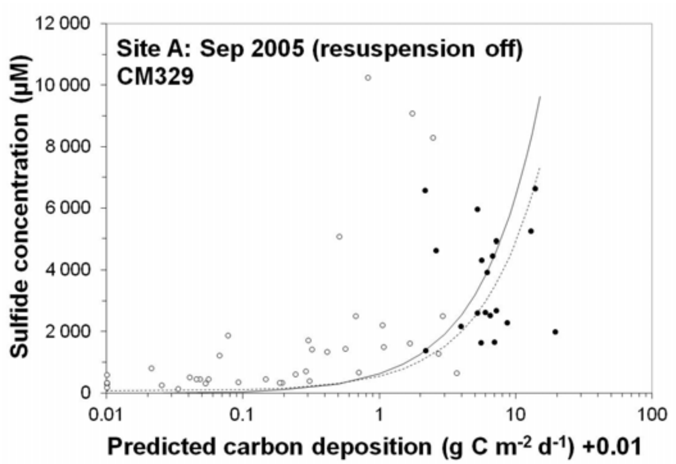


Fig. 47. Relationship among study sites between the maximum predicted deposition rate (using DEPOMOD) and the maximum observed sediment sulfide concentration (from means of subsamples at each sample location). The points represent five study sites, with DEPOMOD predictions based on three current meter deployments at site A and two at each of the other sites, using feed rates at the time of sediment sampling.





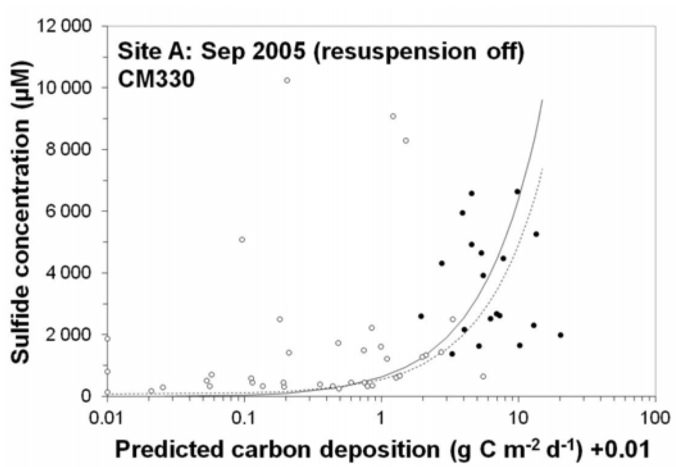


Fig. 48. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during September 2005, resuspension off) and sediment sulfide concentrations (on 22 September 2005) at site A (means of three subsamples per sampling location), using three current meter deployments (CM324, CM329, CM330). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. Black circles are sampling points under the cage array; open circles are sampling points outside the cage array. Lines represent equations for the relationship between these parameters from Hargrave (2010).

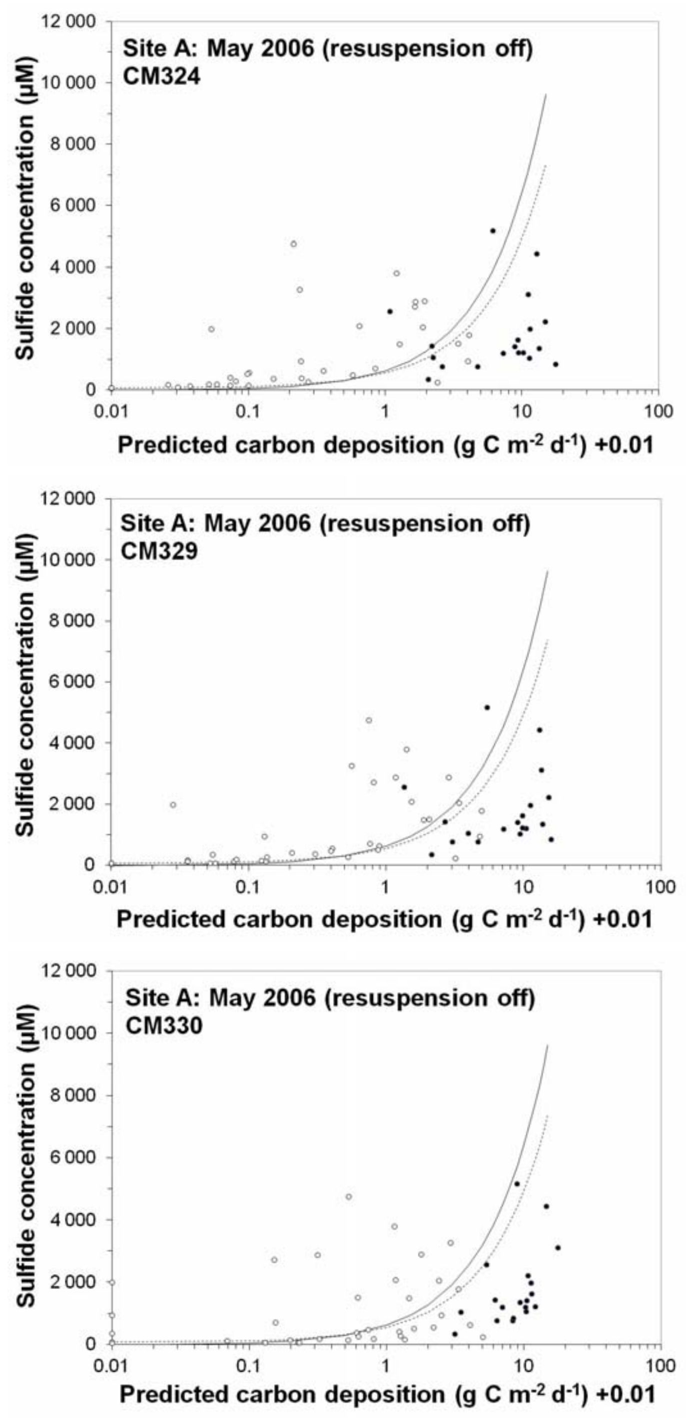
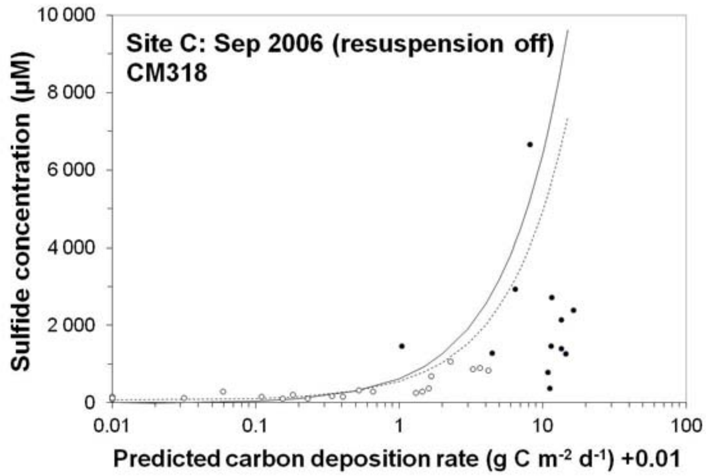


Fig. 49. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during May 2006, resuspension off) and sediment sulfide concentrations (on 24 May 2006) at site A (means of three subsamples per sampling location), using three current meter deployments (CM324, CM329, CM330). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. Black circles are sampling points under the cage array; open circles are sampling points outside the cage array. Lines represent equations for the relationship between these parameters from Hargrave (2010).



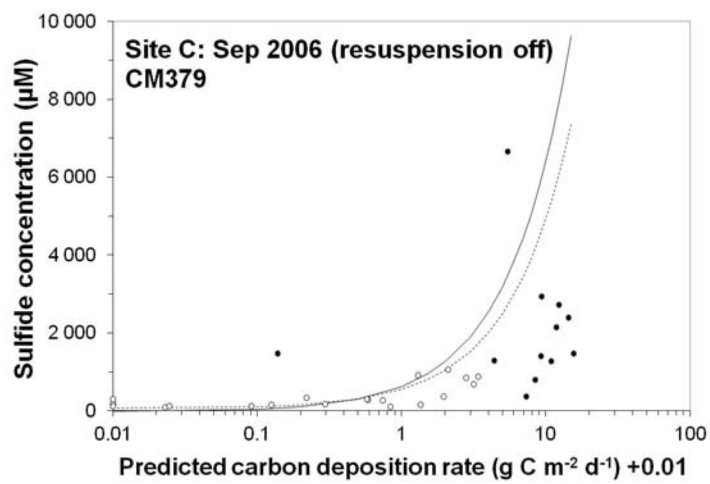


Fig. 50. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during September 2006, resuspension off) and sediment sulfide concentrations (on 12 September 2006) at site C (means of three subsamples per sampling location), using two current meter deployments (CM318 and CM379). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. Black circles are sampling points under the cage array; open circles are sampling points outside the cage array. Lines represent equations for the relationship between these parameters from Hargrave (2010).

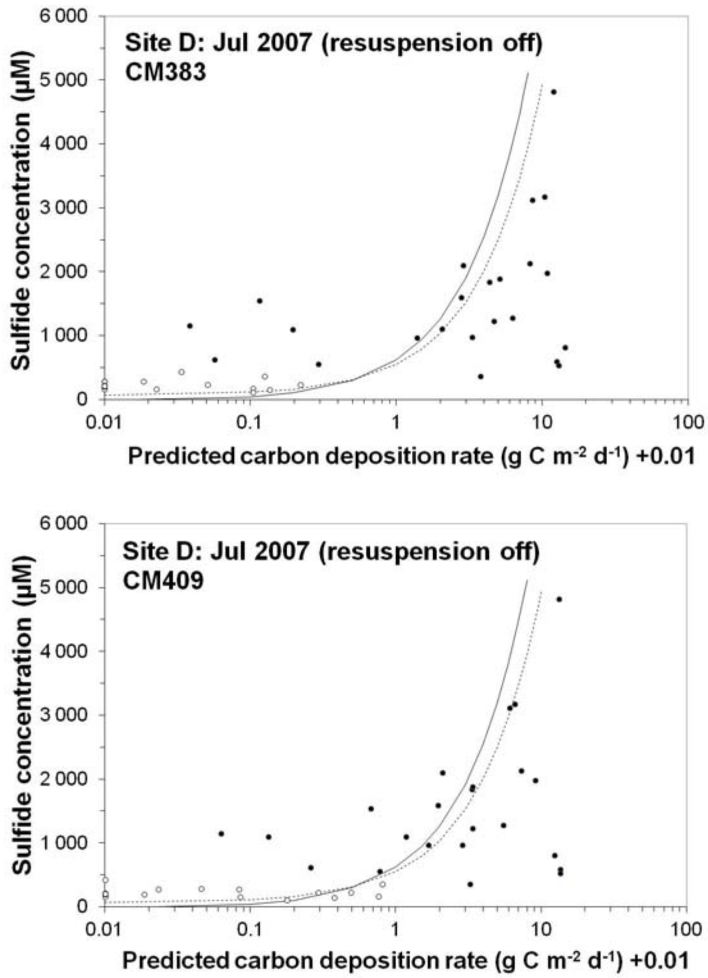


Fig. 51. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during 24 June–24 July 2007, resuspension off) and sediment sulfide concentrations (on 24 July 2007) at site D (means of three subsamples per sampling location), using two current meter deployments (CM383 and CM409). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. Black circles are sampling points under the cage array; open circles are sampling points outside the cage array. Lines represent equations for the relationship between these parameters from Hargrave (2010).

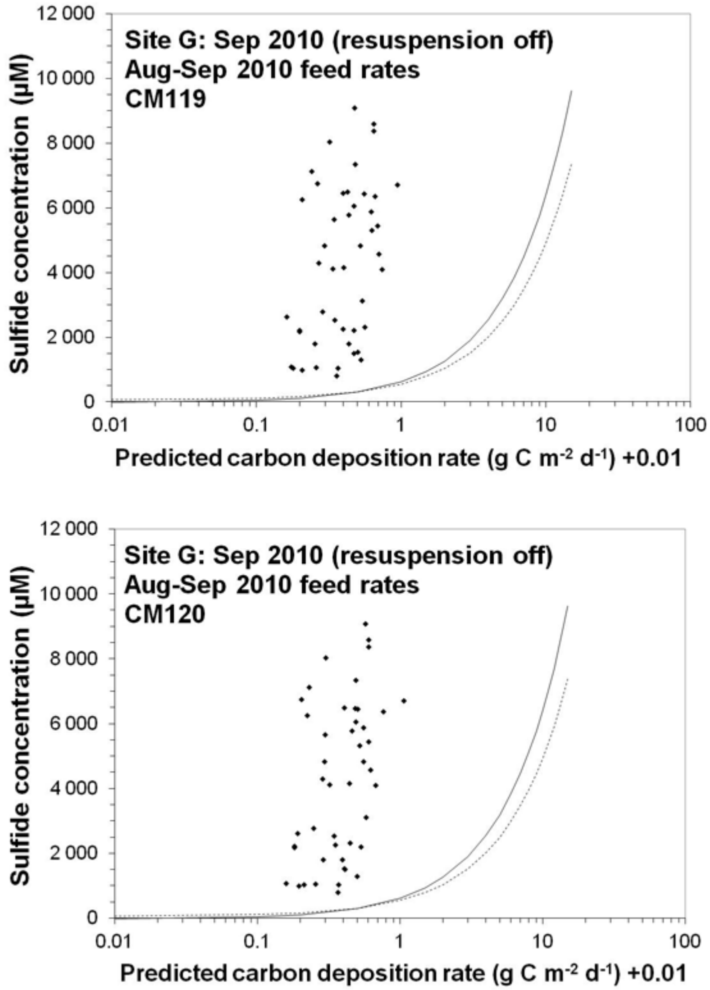
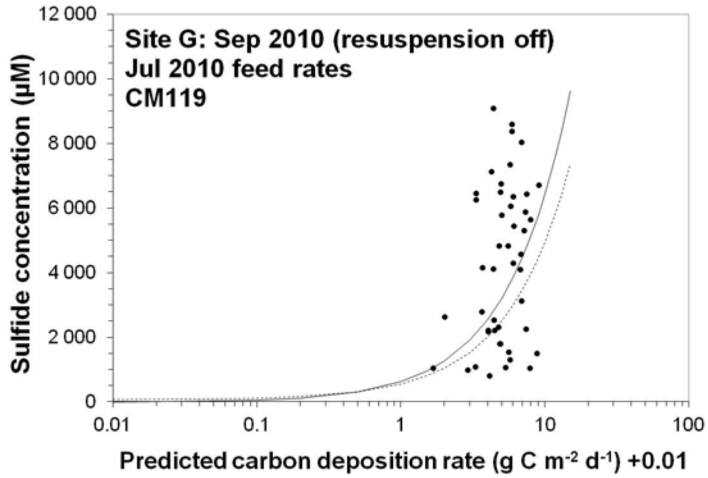


Fig. 52. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during 8 August–11 September 2010, resuspension off) and sediment sulfide concentrations (Tier 2 sampling on 8 September 2010) at site G (means of three subsamples per sampling location), using two current meter deployments (CM119 and CM120). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. All sampling points were under the cage array, extending to the outer perimeter of the array (there were no sampling points outside the cage array). Lines represent equations for the relationship between these parameters from Hargrave (2010).



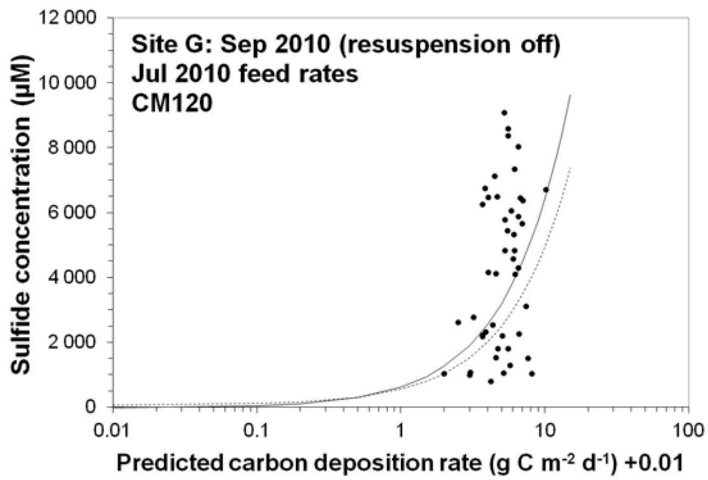
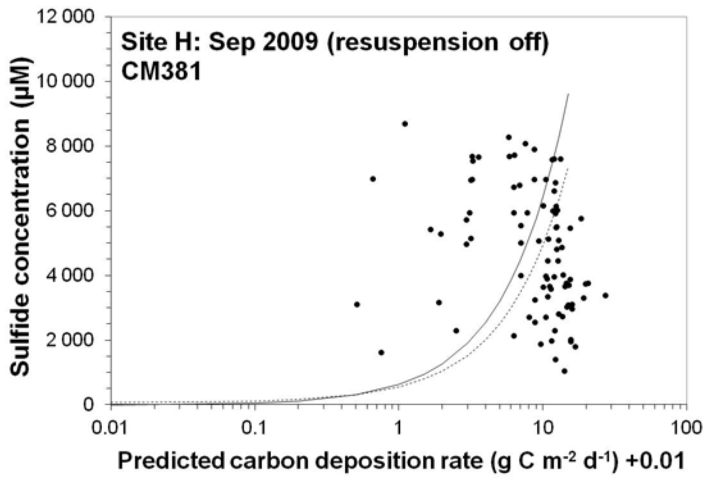


Fig. 53. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during July 2010, resuspension off) and sediment sulfide concentrations (Tier 2 sampling on 8 September 2010) at site G (means of three subsamples per sampling location), using two current meter deployments (CM119 and CM120). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. All sampling points were under the cage array, extending to the outer perimeter of the array (there were no sampling points outside the cage array). Lines represent equations for the relationship between these parameters from Hargrave (2010).



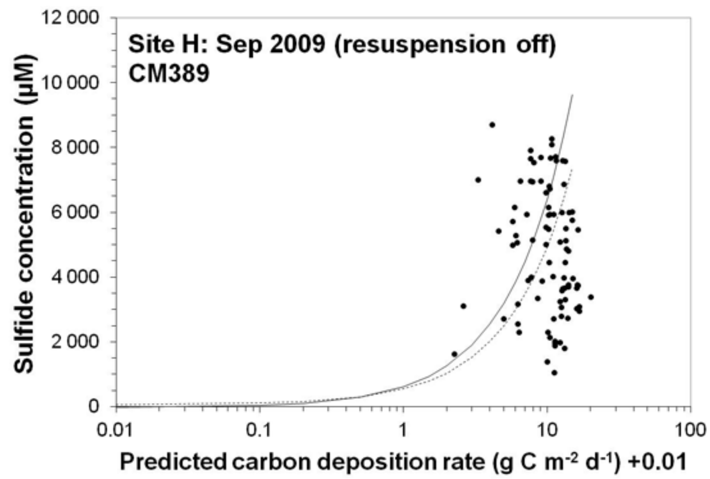


Fig. 54. Relationships between DEPOMOD-predicted carbon deposition rates (using average daily feed rates during 16 August–12 September 2009, resuspension off) and sediment sulfide concentrations (Tier 2 sampling on 11 September 2009) at site H (means of three subsamples per sampling location), using two current meter deployments (CM381 and CM389). The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. All sampling points were under the cage array, extending to the outer perimeter of the array (there were no sampling points outside the cage array). Lines represent equations for the relationship between these parameters from Hargrave (2010).

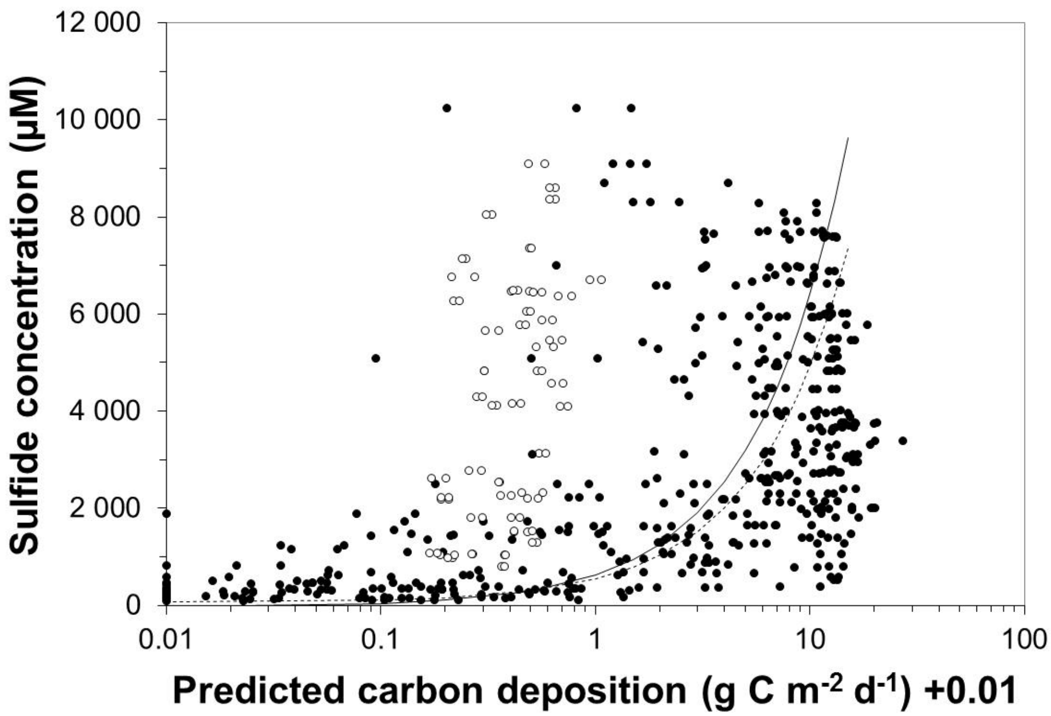


Fig. 55. Relationship between DEPOMOD-predicted carbon deposition rate (resuspension off) and sediment sulfide concentration (means of three subsamples per sampling location): combined data for summer-fall sediment sampling at all five study sites. DEPOMOD was run using feed rates at the time of summer-fall sediment sampling and current velocity data from two to three current meter deployments at each site. The carbon deposition predictions are for the DEPOMOD grid cell corresponding to each sediment sampling location. Lines represent equations for the relationship between these parameters from Hargrave (2010). Black circles are sites A (September 2005 sediment sampling), C, D, and H. Open circles are site G (DEPOMOD predictions using 8 August – 11 September 2010 feed rates). Not included are site A (May 2006 sediment sampling) and site G (DEPOMOD predictions using July 2010 feed rates).

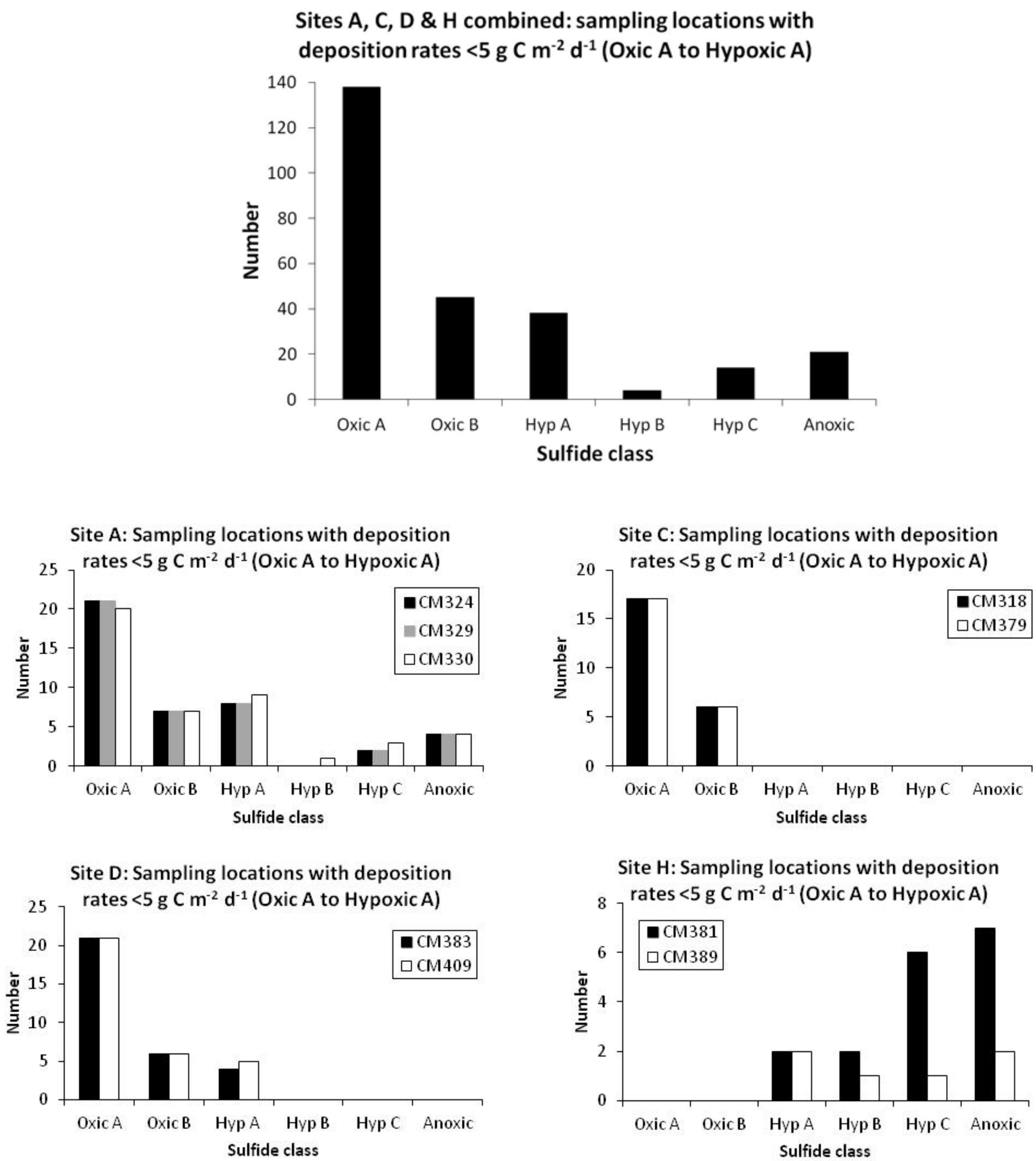


Fig. 56. Histograms of the numbers of sampling locations with DEPOMOD predicted carbon deposition rates <5 g C m^{-2} d^{-1} (Oxic A to Hypoxic A), classed according to sulfide concentration (mean of three subsamples) observed at each location (see Table 1) at sites A (September 2005), C, D, and H combined (top) and at individual sites. There were no sampling locations outside the cage array at site H.

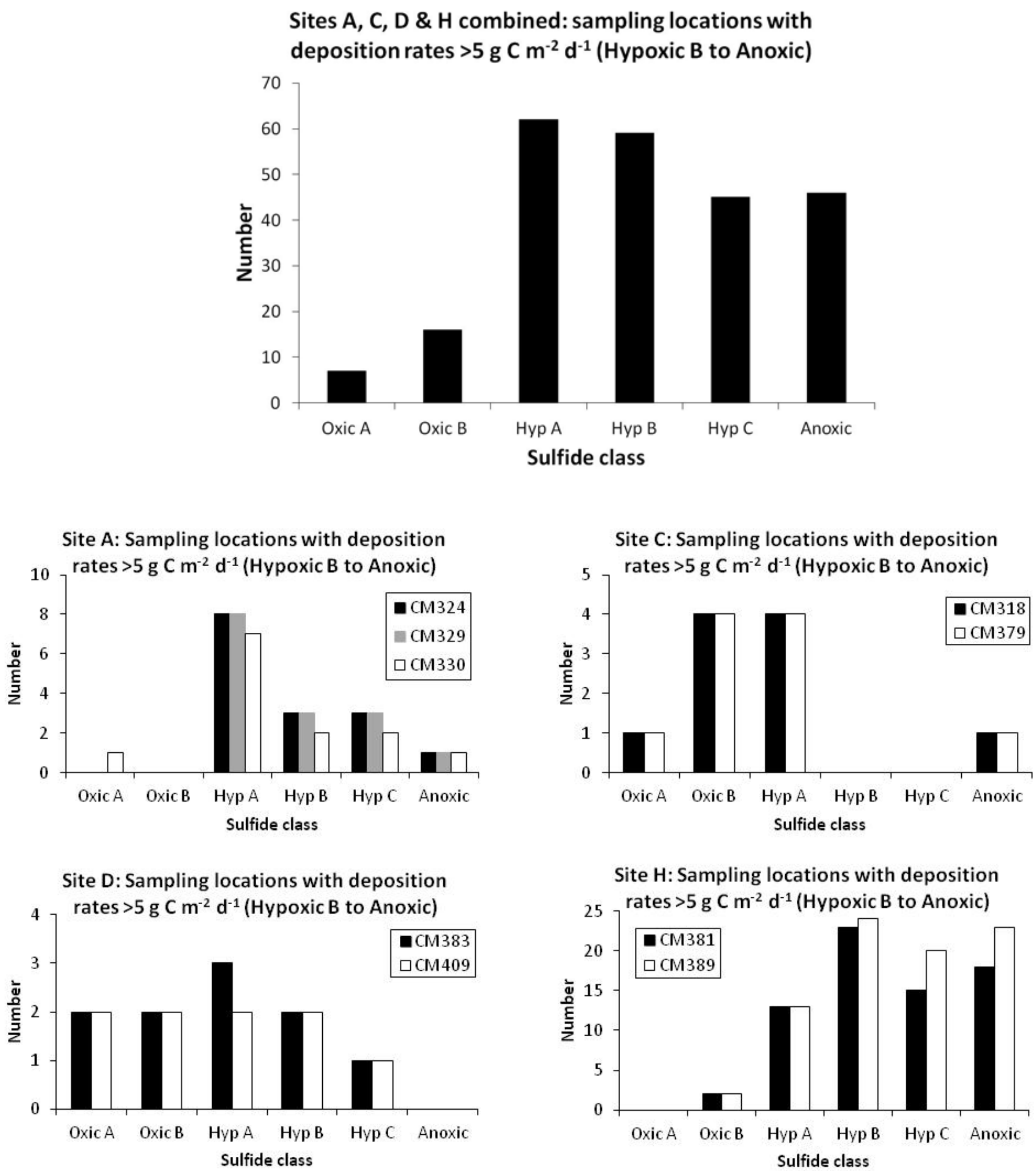


Fig. 57. Histograms of the numbers of sampling locations with DEPOMOD predicted carbon deposition rates >5 g C m^{-2} d^{-1} (Hypoxic B to Anoxic), classed according to the sulfide concentration (mean of three subsamples) observed at each location (see Table 1) at sites A (September 2005), C, D, and H combined (top) and at individual sites. There were no sampling locations outside the cage array at site H.

Appendix A. Additional Analyses of the Relationship between Predicted Carbon Deposition Rate and Sediment Sulfide Concentration

The data for DEPOMOD predicted deposition rates (with resuspension off, using feed rates at the time of sediment sampling) and sulfide concentrations at the sediment sampling locations at sites A (September 2005), C, D, and H (see Fig. 48-51, 54, and 55 of the main report) were replotted on a log-log scale (Fig. A1-A2). Site G was not included, since the DEPOMOD predictions for that site using the feed rates at the time of sediment sampling were known to be inaccurate (see main report).

The conclusions of this analysis were:

- Measured sediment sulfide increases with the DEPOMOD predicted carbon deposition rate.

- The functional relationship is a power curve (log-log).

- For sites A, C, D, and H combined, at sampling locations where DEPOMOD predicted deposition rates are >5 g C m^{-2} d^{-1} (i.e. Hypoxic B to Anoxic), approximately 63% of the observed sulfide concentrations are >3,000 µM (i.e. Hypoxic B to Anoxic) (see Fig. A3); i.e. the prediction of a potential benthic concern is supported.

- This percentage is different for individual sites:
  - 63% is an overestimate for Site C and D and an underestimate for Site H
  - At two of four sites (sites C and D) the predicted area of concern was much greater than the observed impacted area.

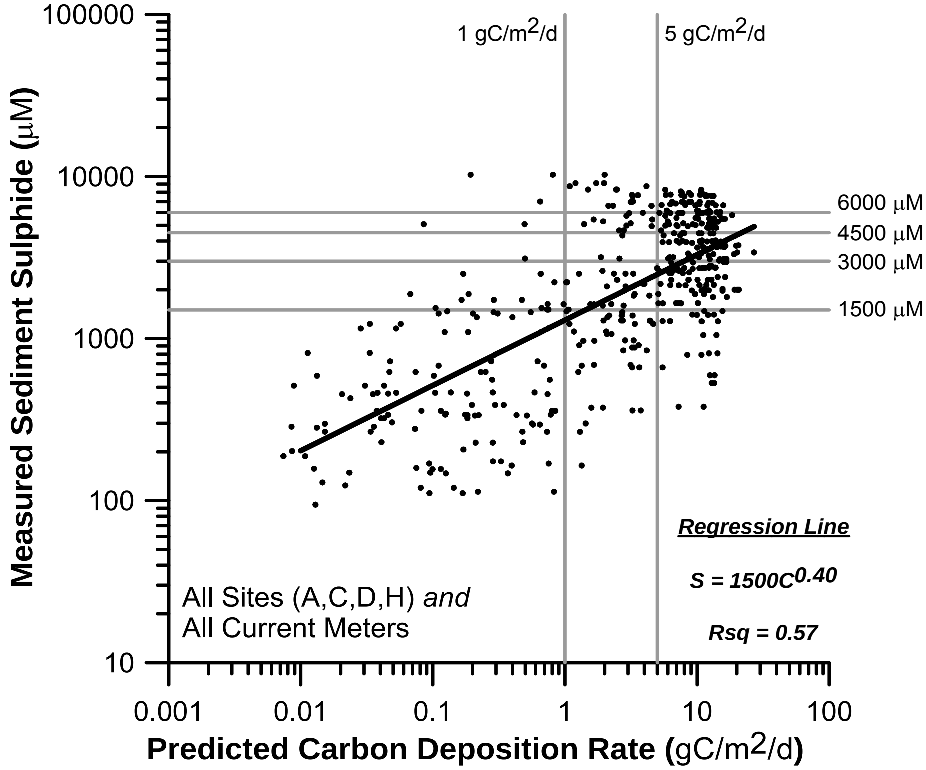


Fig. A1. Log-log plot of DEPOMOD predicted carbon deposition rates (resuspension off) versus sediment sulfide measurements (means of three subsamples) at sampling locations at sites A (September 2005), C, D, and H combined.

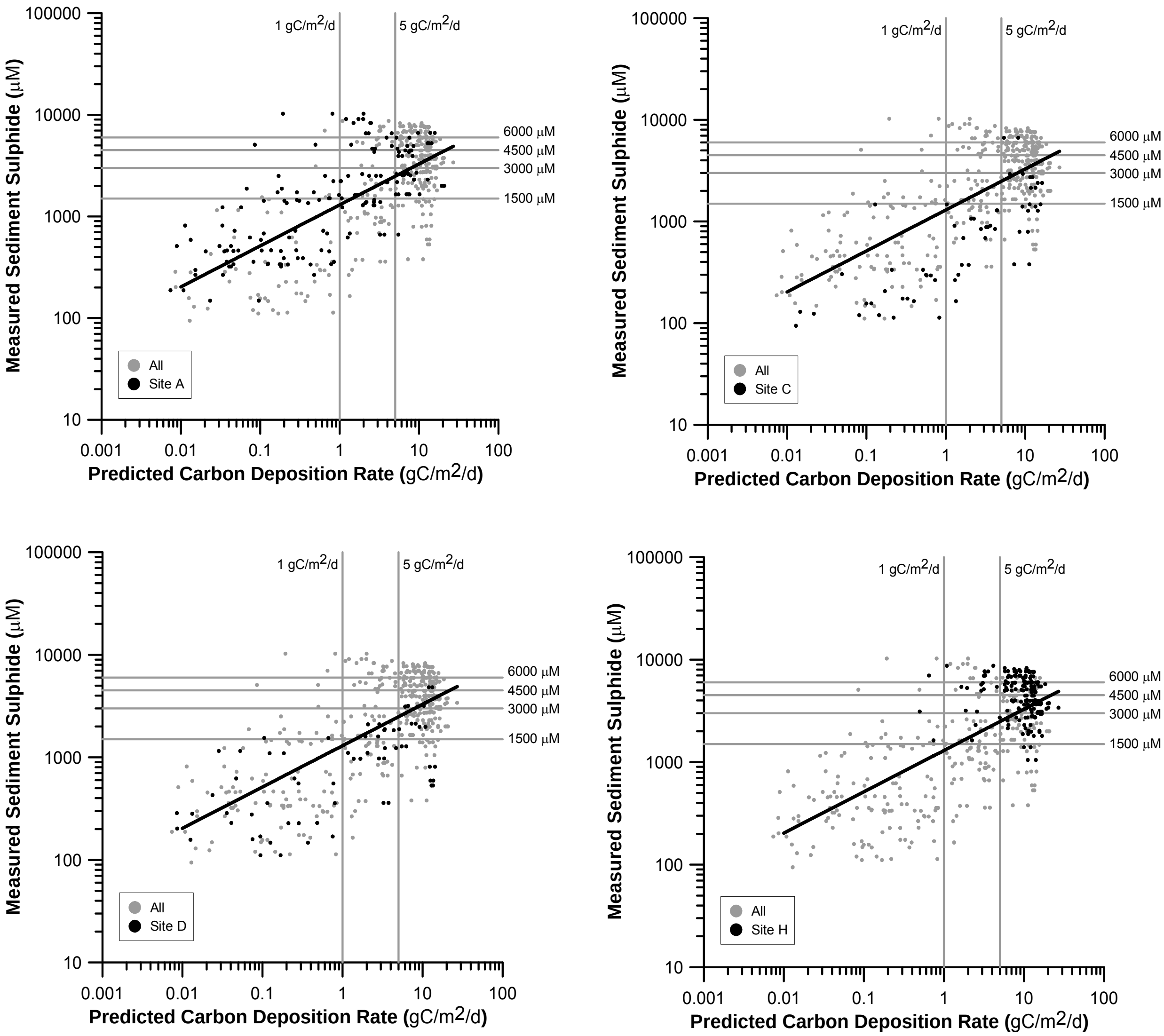


Fig. A2. Log-log plots of DEPOMOD predicted carbon deposition rates (resuspension off) versus sediment sulfide measurements (means of three subsamples) at sampling locations at sites A (September 2005), C, D, and H.

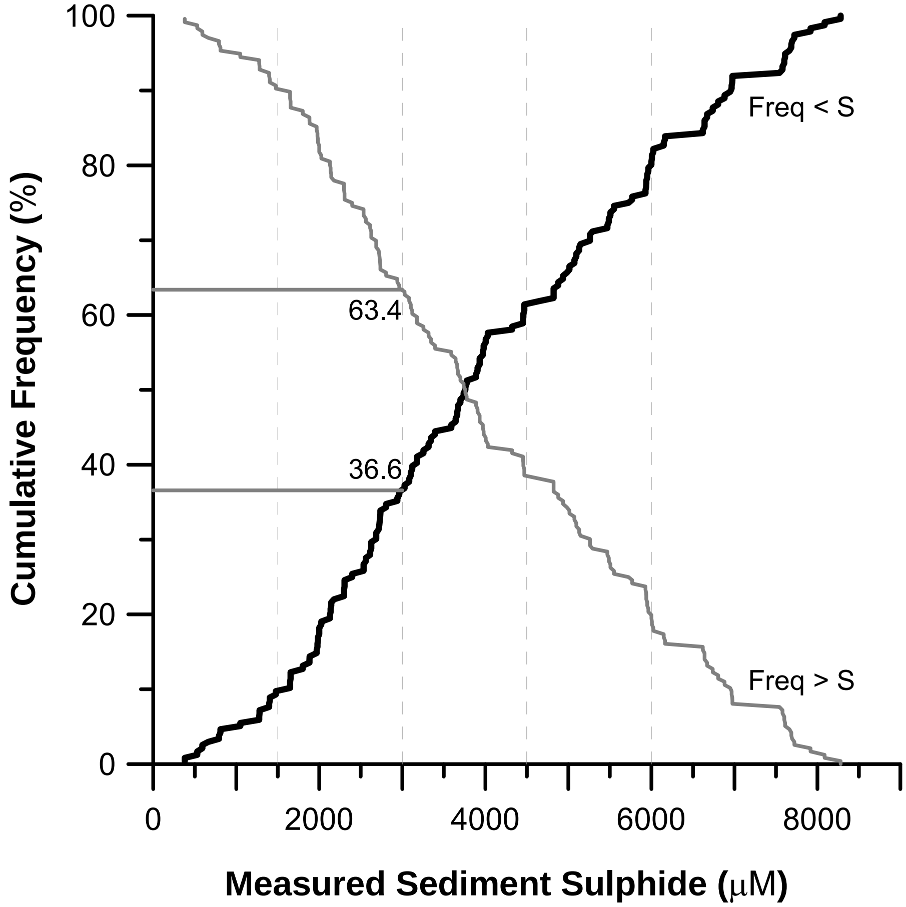


Fig. A3. Cumulative frequency of measured sediment sulfide concentrations (means of three subsamples) for sampling locations with DEPOMOD predicted deposition rates >5 g C m^{-2} d^{-1} (Hypoxic B to Anoxic) at sites A (September 2005), C, D, and H combined. The dark line shows the cumulative frequency of sampling locations with sulfide concentrations less than the value on the x-axis and the grey line shows the frequency of sulfide concentrations greater than the value on the x-axis. Of the sampling locations with predicted deposition rates >5 g C m^{-2} d^{-1}, 63% had measured sulfide values >3,000 µM (Hypoxic B to Anoxic), while 37% had sulfide values ≤3,000 µM (Oxic A to Hypoxic A).

Appendix B. Effects of Tidal Variation in Sea Level on DEPOMOD Predictions

DEPOMOD assumes a temporally constant sea level (i.e. constant water column depth), equivalent to the seafloor depth (depths below chart datum from the bathymetry data) plus the mean tidal height above chart datum. Cromey et al. (2002) noted that use of a temporally constant sea level should not affect the accuracy of predictions in areas where the tidal range is small relative to the water depth, such as in Scotland. However, in our southwestern New Brunswick (SWNB) study sites, the tidal range is quite large relative to the water depth at salmon farms (Table B1).

The effects of varying sea level were investigated by running DEPOMOD, with resuspension off, using the sea level (tidal height above chart datum) at mean low tide, mean tide, and mean high tide. The predicted maximum carbon deposition rates and the spatial extent of the seafloor area were then compared with predicted deposition rates >5 g C m^{-2} d^{-1} for the three sea levels at each site. One set of current velocity data was used per site. All other parameter values were the same as in the main report. At all five sites, the feed rates used were from the fall, at the time of sediment sampling (see main report).

In all cases, 100% of the waste was deposited on the seafloor within the model domain. The maximum deposition rates were lowest at high tide, when the water column depth is greatest. At low tide, the maximum deposition rates were 1.0-1.6 times higher than at high tide (Fig. B1). However, tidal height had little or no effect on the spatial extent of the seafloor area with deposition rates >5 g C m^{-2} d^{-1} (Fig. B2).

<u>Reference</u>

Cromey, C.J., Nickell, T.D., and Black, K.D. 2002. DEPOMOD – Modelling the deposition and biological effects of waste solids from marine cage farms. Aquaculture 214: 211-239.

Table B1. Tidal heights at study sites at mean low tide, mean tide, and mean high tide. The seafloor depth below chart datum (CD, lowest normal tide) is the average of CHS soundings taken under the cage array. Tidal data are from the nearest CHS reference or secondary port (Canadian Tide and Current Tables. Volume 1: Atlantic Coast and Bay of Fundy).

Site	Seafloor depth under cage array (m below CD)	Tidal height (m above CD)		
		Mean low tide	Mean tide	Mean high tide
A	16.2	0.9	4.0	7.0
C	19.5	1.1	3.8	6.6
D	14.6	1.1	3.8	6.6
G	15.0	0.9	3.9	6.9
H	22.2	1.1	3.8	6.6

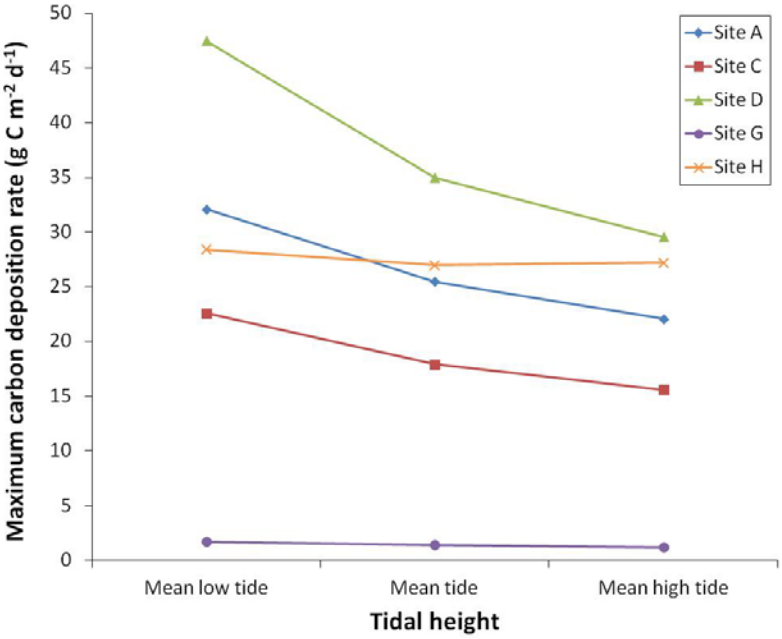


Fig. B1. Tidal height (sea level) versus DEPOMOD predicted maximum predicted carbon deposition rate (with resuspension off) at five study sites.

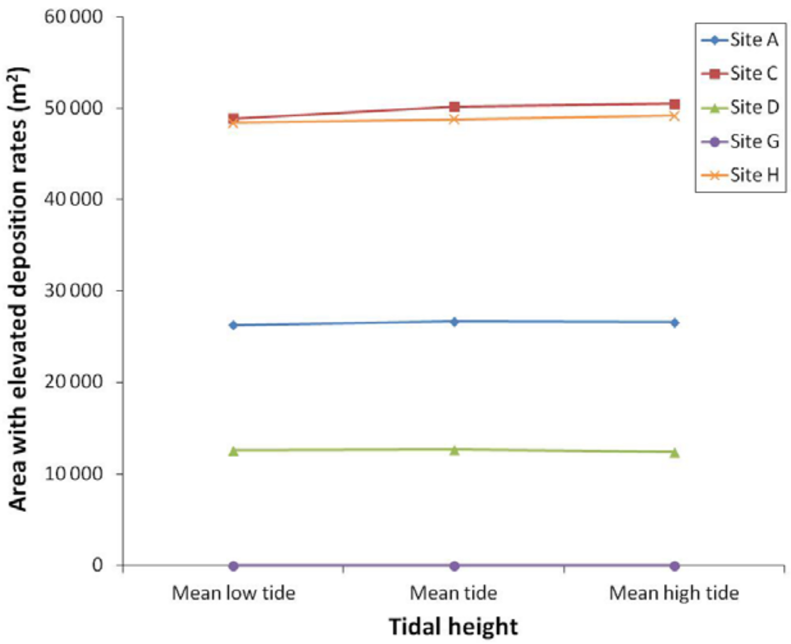


Fig. B2. Tidal height (sea level) versus DEPOMOD predictions of the spatial extent of seafloor area with carbon deposition rates >5 g C m^{-2} d^{-1} (with resuspension off) at five study sites.

Appendix C. Effects of Feed Wastage Rates on DEPOMOD Predictions

To determine the sensitivity of DEPOMOD predictions to variations in the feed wastage rates, the model was run at five sites, with resuspension off, at feed wastage rates (as % of food fed) of 1, 5, 10, and 15%, in addition to the default value of 3%. One set of current meter data was used per site. All other parameter values were the same as in the main report. At all five sites, the feed rates were from the summer-fall, at the time of sediment sampling (see main document).

The predicted total amount of waste produced increased linearly as the feed wastage rate increased (Fig. C1). In all cases, a five-fold increase in the feed waste rate, from 3% to 15%, resulted in an increase in the total amount of waste produced by a factor of 2.3. The differences in waste amounts between sites reflected the different feed rates at each site (see Table 8 of the main report). In all cases, 100% of the waste was deposited on the seafloor within the model domain.

Contour plots of the predicted carbon deposition rates for each feed wastage rate at the five sites are shown in Fig. C2-C6. Plots of the areas with elevated deposition rates (>5 g C m^{-2} d^{-1}) at sites A, C, D, and H are shown in Fig. C7; there were no areas with elevated deposition rates at site G.

Increasing the feed wastage rate resulted in large increases in the maximum predicted carbon deposition rates; the relationship was linear, except at the very lowest feed wastage rates (1-3%) at sites C and H (Fig. C8). A five-fold increase in the feed wastage rate, from 3% to 15%, resulted in the maximum predicted carbon deposition rate increasing by factors of 2.3-3.6. Chamberlain and Stucchi (2007) reported that the predicted carbon deposition rate at the cage edge almost doubled when the feed wastage rate was increased from 5% to 10%, as well as from 10% to 15%, when using DEPOMOD at a salmon farm in British Columbia. In the present study, increasing the feed wastage rate from 5% to 10% resulted in the maximum predicted carbon deposition rate increasing by factors of 1.5-1.8, while increasing the feed wastage rate from 10% to 15% resulted in the maximum carbon deposition rate increasing by factors of 1.3-1.4.

Increasing the feed wastage rate resulted in smaller increases in the area of seafloor with predicted carbon deposition rates >5 g C m^{-2} d^{-1} (Fig. C9). A five-fold increase in the feed wastage rate, from 3% to 15%, resulted in the area of seafloor with predicted carbon deposition rates >5 g C m^{-2} d^{-1} increasing by factors of 1.2-1.6, except at site G, where there were no areas with carbon deposition rates >5 g C m^{-2} d^{-1} at any of the feed wastage rates.

Reference

Chamberlain, J. and Stucchi, D. 2007. Simulating the effects of parameter uncertainty on waste model predictions of marine finfish aquaculture. Aquaculture 272: 296-311.

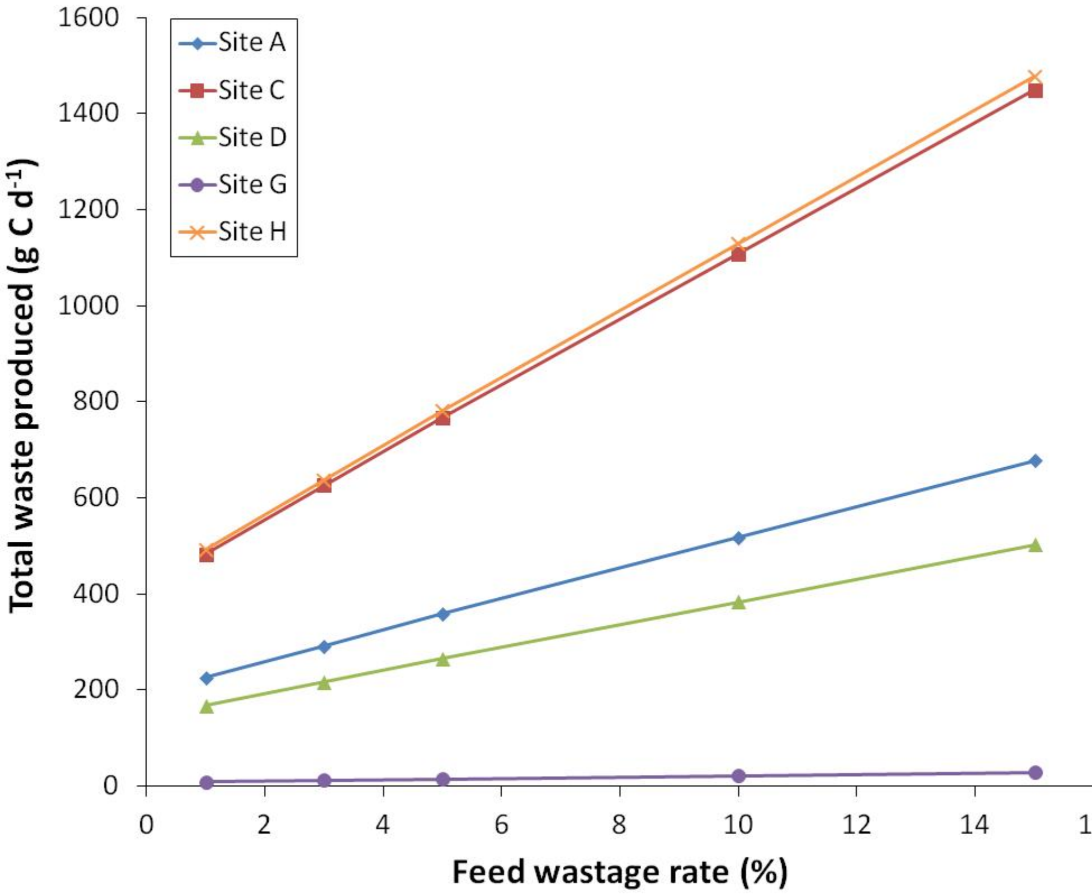


Fig. C1. DEPOMOD predictions of feed wastage rate versus total waste produced at five study sites.

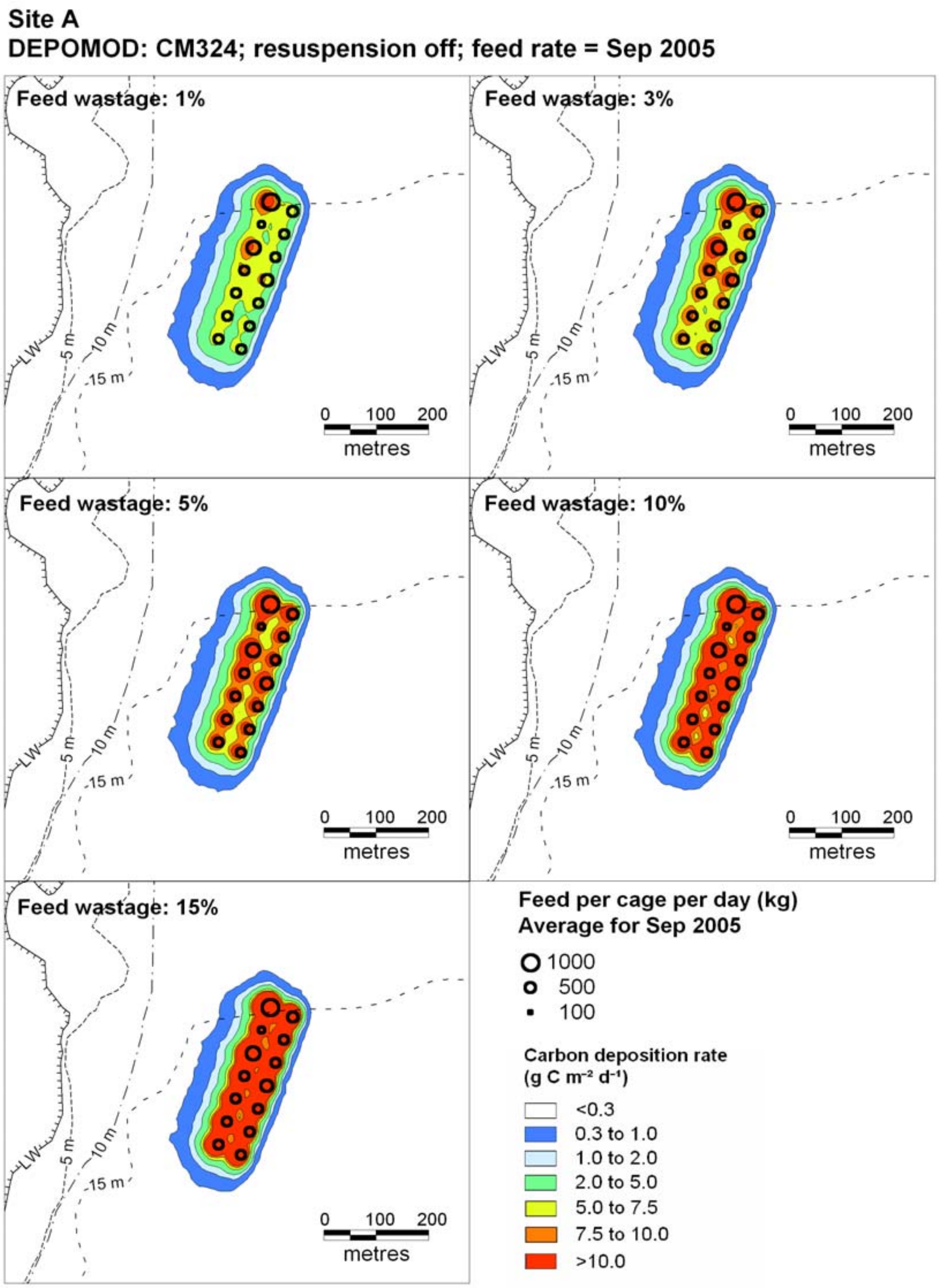


Fig. C2. Contour plots of DEPOMOD predicted carbon deposition rates at site A, using feed wastage rates (% of food fed) of 1, 3, 5, 10, and 15%, with resuspension off. All plots use current velocity data from deployment CM324 and average feed rates per cage during September 2005. Approximate cage locations are shown by circles, with circle sizes indicating the average feed rate per day in each cage during September 2005.

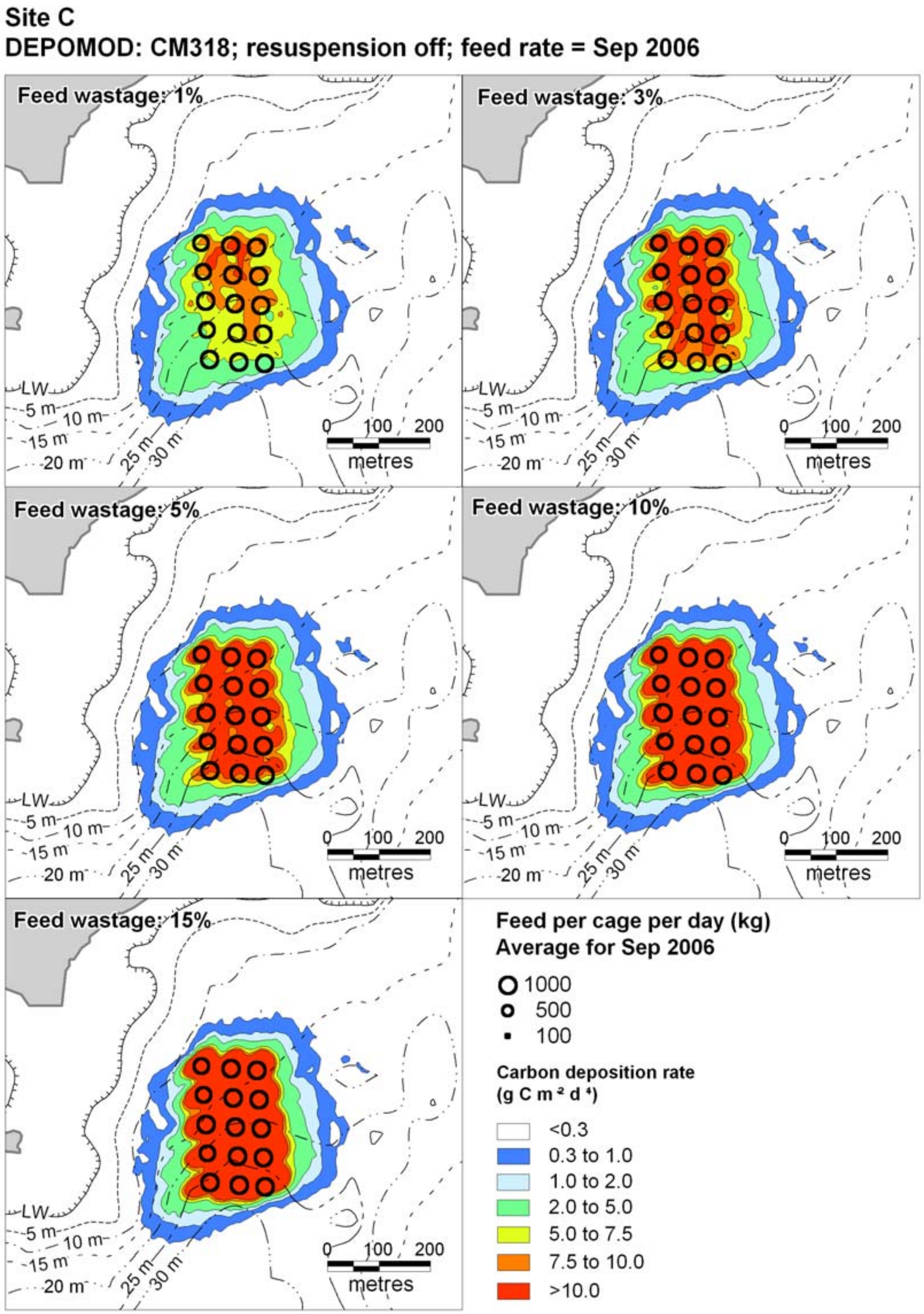


Fig. C3. Contour plots of DEPOMOD predicted carbon deposition rates at site C, using feed wastage rates (% of food fed) of 1, 3, 5, 10, and 15%, with resuspension off. All plots use current velocity data from deployment CM318 and average feed rates per cage during September 2006. Approximate cage locations are shown by circles, with circle sizes indicating the average feed rate per day in each cage during September 2006.

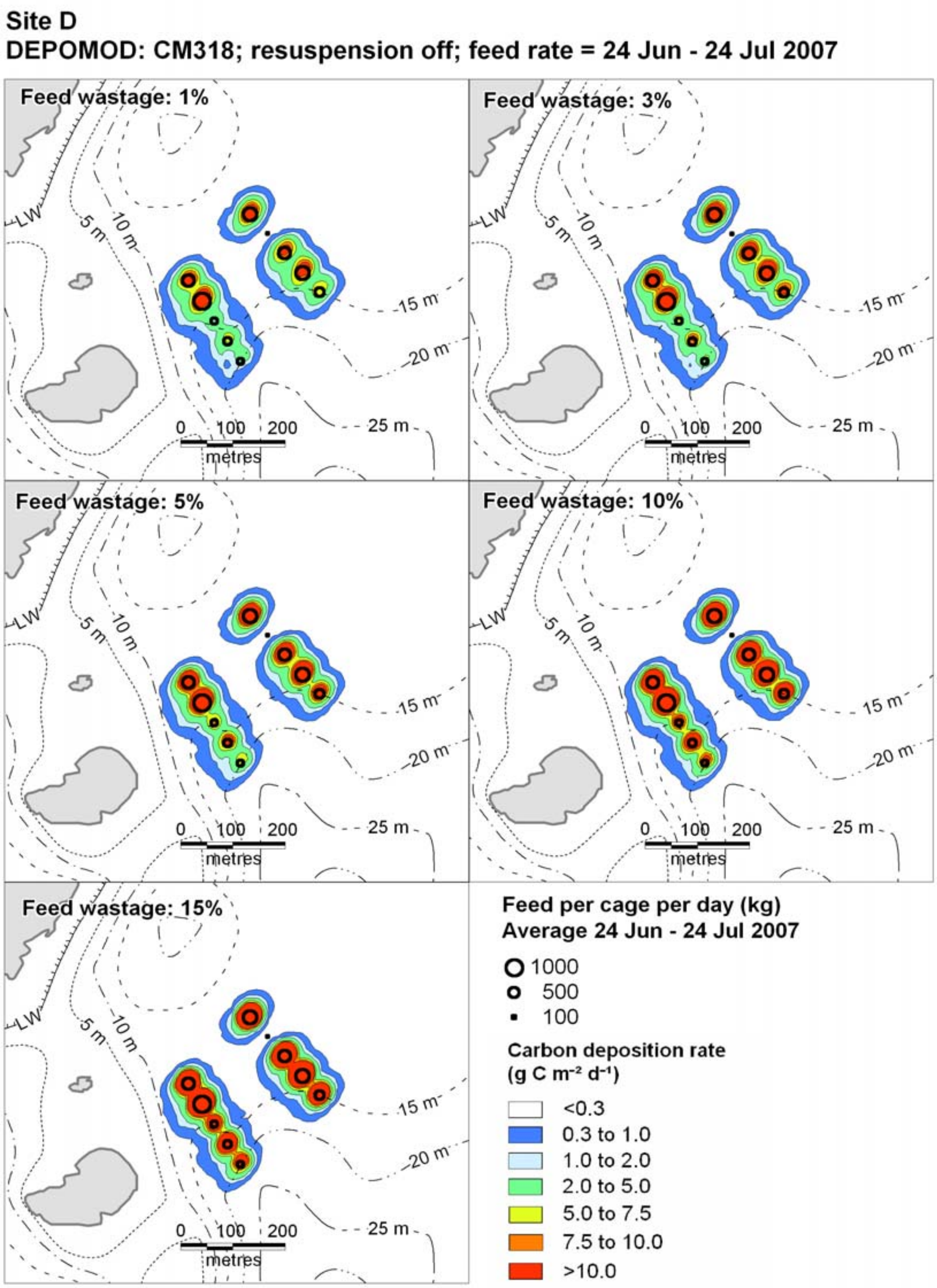


Fig. C4. Contour plots of DEPOMOD predicted carbon deposition rates at site D, using feed wastage rates (% of food fed) of 1, 3, 5, 10, and 15%, with resuspension off. All plots use current velocity data from deployment CM383 and average feed rates per cage during 24 June-24 July 2007. Approximate cage locations are shown by circles, with circle sizes indicating the average feed rate per day in each cage during 24 June-24 July 2007.

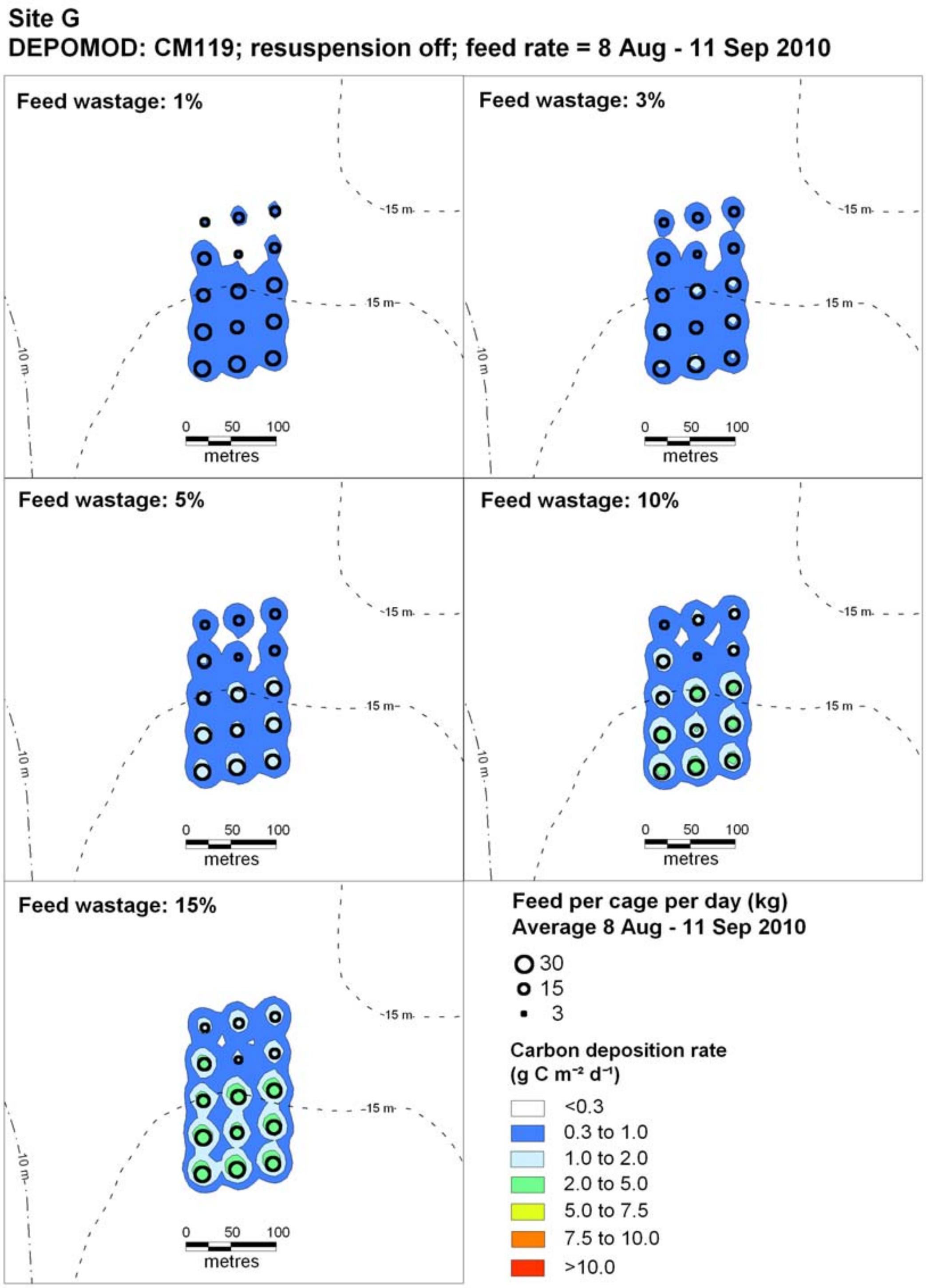


Fig. C5. Contour plots of DEPOMOD predicted carbon deposition rates at site G, using feed wastage rates (% of food fed) of 1, 3, 5, 10, and 15%, with resuspension off. All plots use current velocity data from deployment CM119 and average feed rates per cage during 8 August-11 September 2010. Approximate cage locations are shown by circles, with circle sizes indicating the average feed rate per day in each cage during 8 August-11 September 2010.

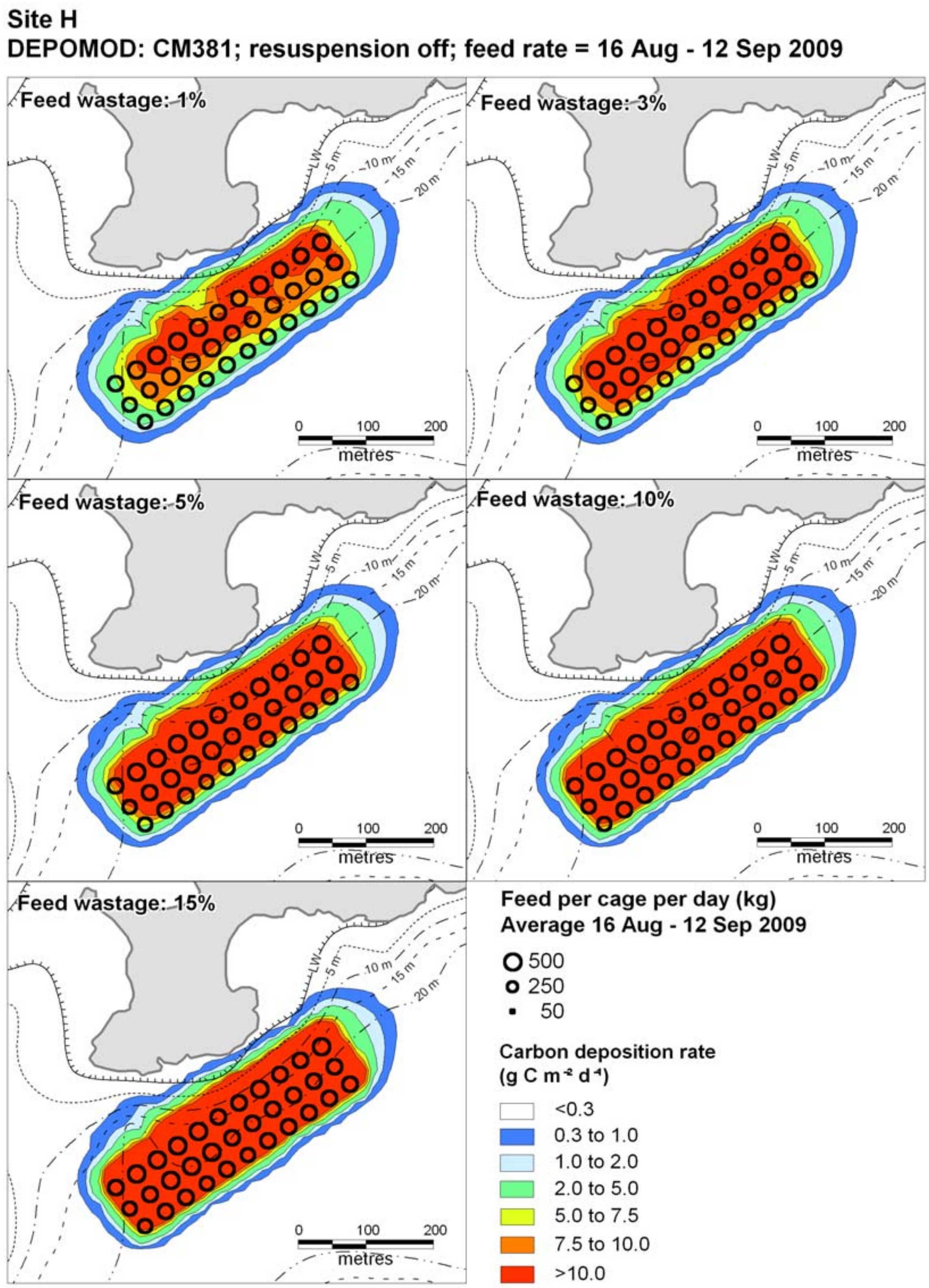


Fig. C6. Contour plots of DEPOMOD predicted carbon deposition rates at site H, using feed wastage rates (% of food fed) of 1, 3, 5, 10, and 15%, with resuspension off. All plots use current velocity data from deployment CM119 and average feed rates per cage during 16 August-12 September 2009. Approximate cage locations are shown by circles, with circle sizes indicating the average feed rate per day in each cage during 16 August-12 September 2009.

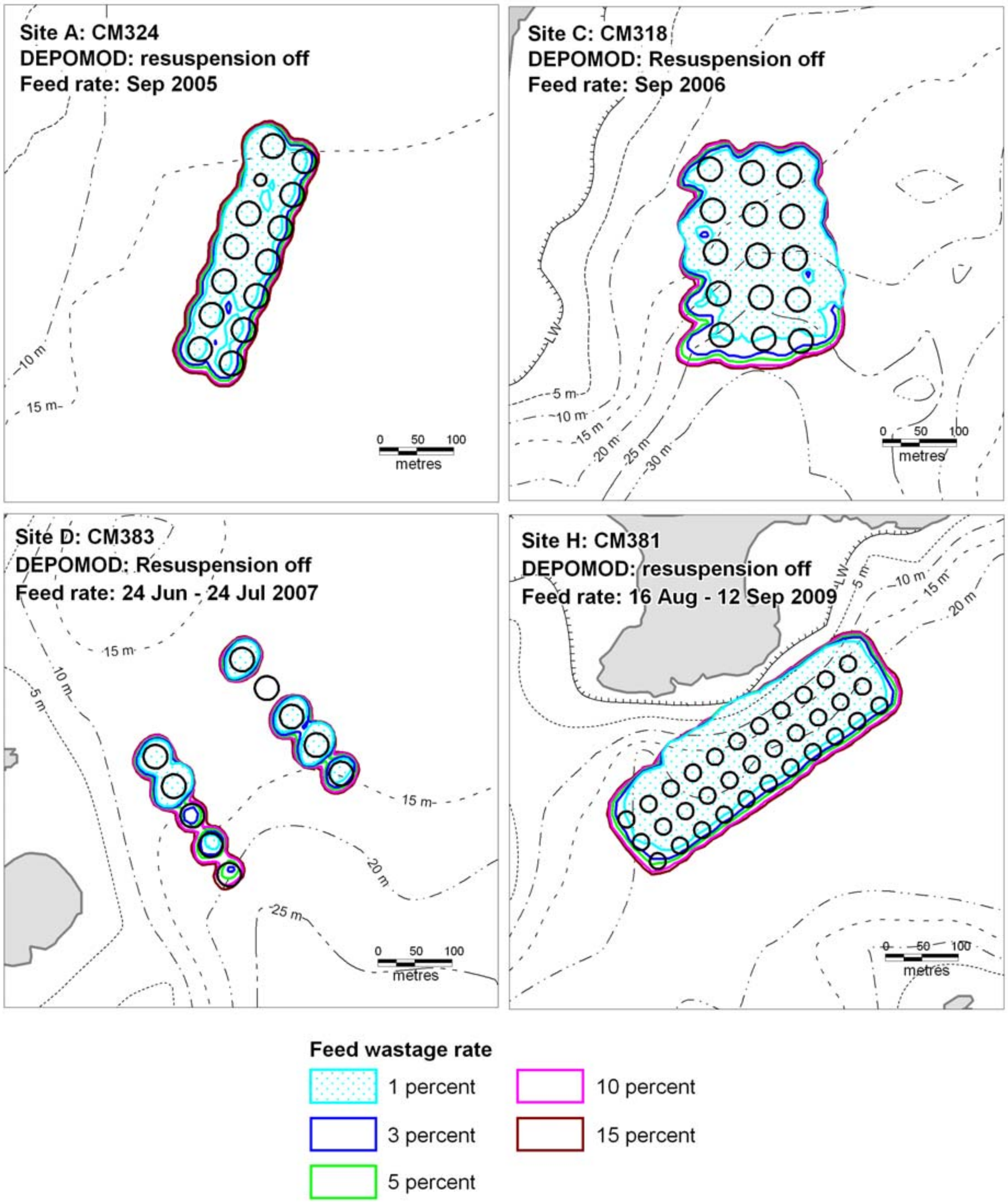


Fig. C7. DEPOMOD predictions (with resuspension off) of areas with elevated carbon deposition rates (>5 g C m^{-2} d^{-1}), using feed wastage rates (% of food fed) of 1, 3, 5, 10, and 15%, at four salmon farms in SWNB. There were no areas with elevated deposition rates predicted at a fifth study site (site G) when using feed rates at the time of sediment sampling. Black circles indicate cage locations and sizes.

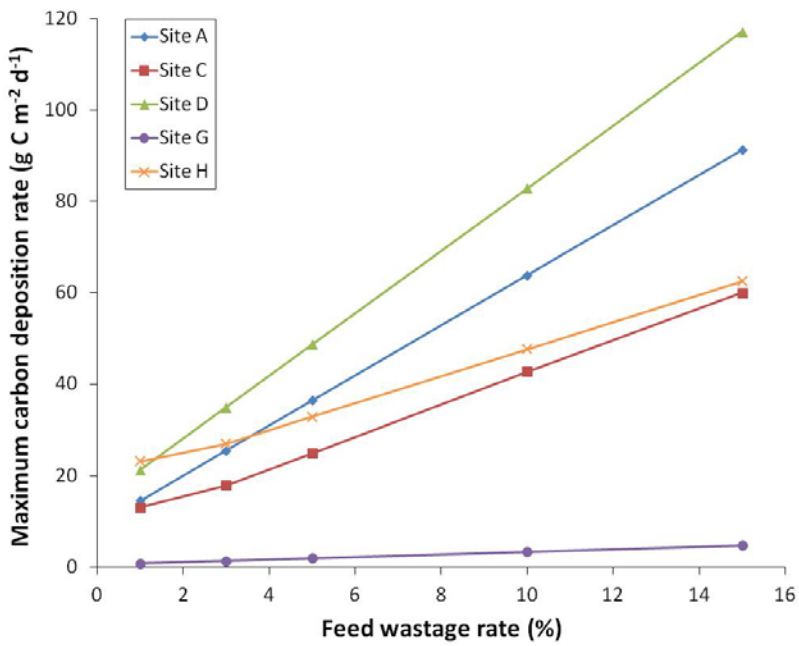


Fig. C8. DEPOMOD predictions (with resuspension off) of feed wastage rate versus maximum predicted carbon deposition rate at five study sites.

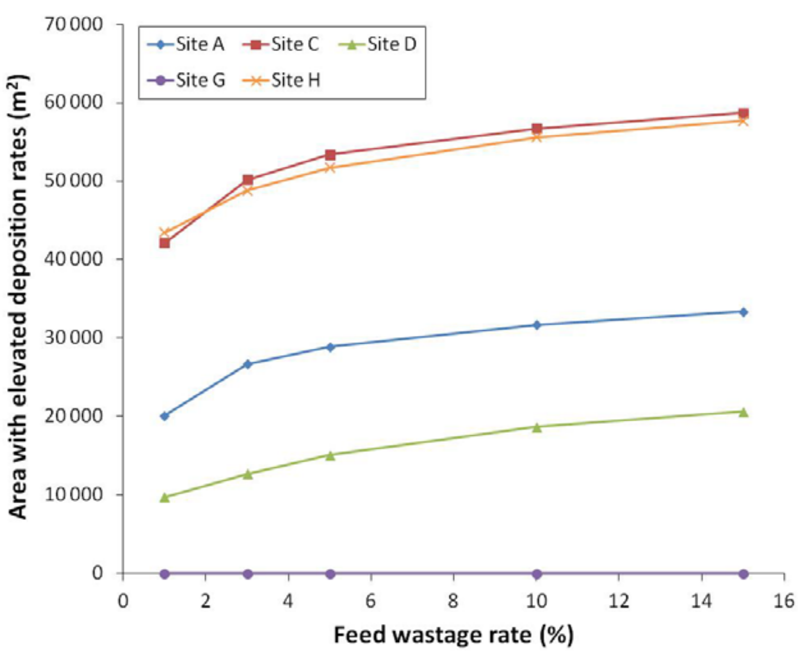


Fig. C9. DEPOMOD predictions (with resuspension off) of feed wastage rate versus the spatial extent of seafloor area with carbon deposition rates >5 g C m^{-2} d^{-1} at five study sites.

Appendix D. DEPOMOD Predictions using Revised Feed Characteristics

Revised feed characteristic values, for currently used feed, were provided by M. Szemerda (Cooke Aquaculture, St. George, NB, pers. comm.). The original (based on Stucchi and Chamberlain, unpublished data[1]) and revised values are shown in Table D1. Other particle information was not changed (see Table 2 of main report).

DEPOMOD was run with the revised feed characteristics, using the 2-3 sets of current velocity data per site and feed rates at the time of sediment sampling. The results were compared to those obtained using the original feed characteristics (from the main report).

Using the revised feed characteristics resulted in an approximate doubling of the total waste production at all five sites (Table D2). With resuspension off, all of the wastes were deposited within the model domain at each farm (Table D3). With resuspension on, the percentage of waste deposited within the model domain varied among farms, from very low at site A, to very high at site G (Table D3); these percentages were slightly higher than the corresponding values using the original feed characteristics.

The revised feed characteristics resulted in increases in the predicted areas of elevated impacts (Table D4 and Fig. D1-D11) and in the predicted maximum deposition rates (Table D5), compared to the corresponding values when using the original feed characteristics.

[1] Stucchi, D.J., and Chamberlain, J. 2005. DEPOMOD Canada Methods and Settings V2.0. Fisheries and Oceans Canada, Pacific Region. (unpublished document).

Table D1. DEPOMOD input values for feed characteristics: original and revised values.

Feed characteristic	Original	Revised
Water content of feed (%)	10	5
Digestibility (%)	90	75
Carbon as % of food pellets (dry weight)	57	52

Table D2. DEPOMOD predicted total waste production using original and revised feed characteristics (see Table D1).

Site	Sediment sampling date	Total feed rate (kg d^{-1})	Waste produced per kg feed (kg C)		Total waste produced (kg C d^{-1})	
			Original feed	Revised feed	Original Feed	Revised Feed
A	Sep 05	6,644	0.044	0.091	292	605
C	Sep 06	14,218	0.044	0.091	626	1,294
D	Jul 07	4,927	0.044	0.091	217	448
G	Sep 10	283	0.044	0.091	12	26
H	Sep 09	14,485	0.044	0.091	637	1,318

Table D3. DEPOMOD mass balance calculations using original and revised feed characteristics. The rate of waste released from a farm was calculated from the feeding rate and the estimated rate of waste production per unit of feed, based on the feed and feces characteristics. The rate of waste deposition within the model domain was calculated using the predicted waste deposition rates within each model grid cell. The domain sizes were approximately,1000 ×,1000 m at sites A, C, D, and G, and,2000 ×,2000 m at site H.

						% of waste within the DEPOMOD domain	
Site	Sediment sampling date	CM	Total feed rate (kg d^{-1})	Feed characteristics	Waste produced (kg C d^{-1})	Resuspension off	Resuspension on
A	Sep 05	324	6,644	Original	292	100	<1
		329	6,644	Original	292	100	2
		329	6,644	Original	292	100	4
A	Sep 05	324	6,644	Revised	605	100	4
		329	6,644	Revised	605	100	6
		329	6,644	Revised	605	100	8
C	Sep 06	318	14,218	Original	626	100	<1
		379	14,218	Original	626	100	6
C	Sep 06	318	14,218	Revised	1,294	100	6
		379	14,218	Revised	1,294	100	31
D	Jul 07	383	4,927	Original	217	100	79
		409	4,927	Original	217	100	15
D	Jul 07	383	4,927	Revised	448	100	87
		409	4,927	Revised	448	100	24
G	Sep 10	119	283	Original	12	100	69
		120	283	Original	12	100	88
G	Sep 10	119	283	Revised	26	100	82
		120	283	Revised	26	100	93
H	Sep 09	381	14,485	Original	637	100	22
		389	14,485	Original	637	100	64
H	Sep 09	381	14,485	Revised	1,318	100	42
		389	14,485	Revised	1,318	100	79

Table D4. DEPOMOD predicted areas of elevated benthic impacts (>5 g C m^{-2} d^{-1}) using original and revised feed characteristics (see Table D1). Also shown are the observed areas of elevated sediment sulfide concentration (>3,000 µM).

			Area of elevated benthic impacts (m^2)				
			DEPOMOD: resuspension off		DEPOMOD: resuspension on		
Site	Sediment sampling date	Current meter	original	revised	original	revised	Sulfide concentration >3,000 µM
A	Sep 05	324	26,700	44,700	0	1,100	32,200
		329	25,800	40,200	0	700	
		330	21,400	41,900	0	700	
C	Sep 06	318	50,200	79,400	0	3,300	4,800
		379	48,600	76,100	200	32,200	
D	Jul 07	383	12,700	25,600	10,500	22,900	3,700
		409	10,800	28,100	600	6,200	
G	Sep 10	119	0	0	0	0	17,500
		120	0	0	0	0	
H	Sep 09	381	48,800	63,100	4,800	41,800	48,100
		389	49,600	63,800	39,200	56,300	

Table D5. DEPOMOD predicted maximum carbon deposition rates using original and revised feed characteristics (see Table D1).

			Maximum deposition rate (g C m^{-2} d^{-1})			
			Resuspension off		Resuspension on	
Site	Sediment sampling date	Current meter	original	revised	original	revised
A	Sep 05	324	25.5	39.3	1.9	15.8
		329	24.2	38.2	4.1	15.7
		330	20.4	32.4	3.3	9.7
C	Sep 06	318	17.9	32.4	0.1	10.4
		379	20.2	35.5	6.8	24.1
D	Jul 07	383	35.0	57.3	33.9	56.3
		409	21.8	33.4	10.0	20.9
G	Sep 10	119	1.4	2.4	1.3	2.2
		120	1.4	2.3	1.3	2.2
H	Sep 09	381	27.0	60.7	13.6	45.6
		389	20.1	42.6	18.4	39.6

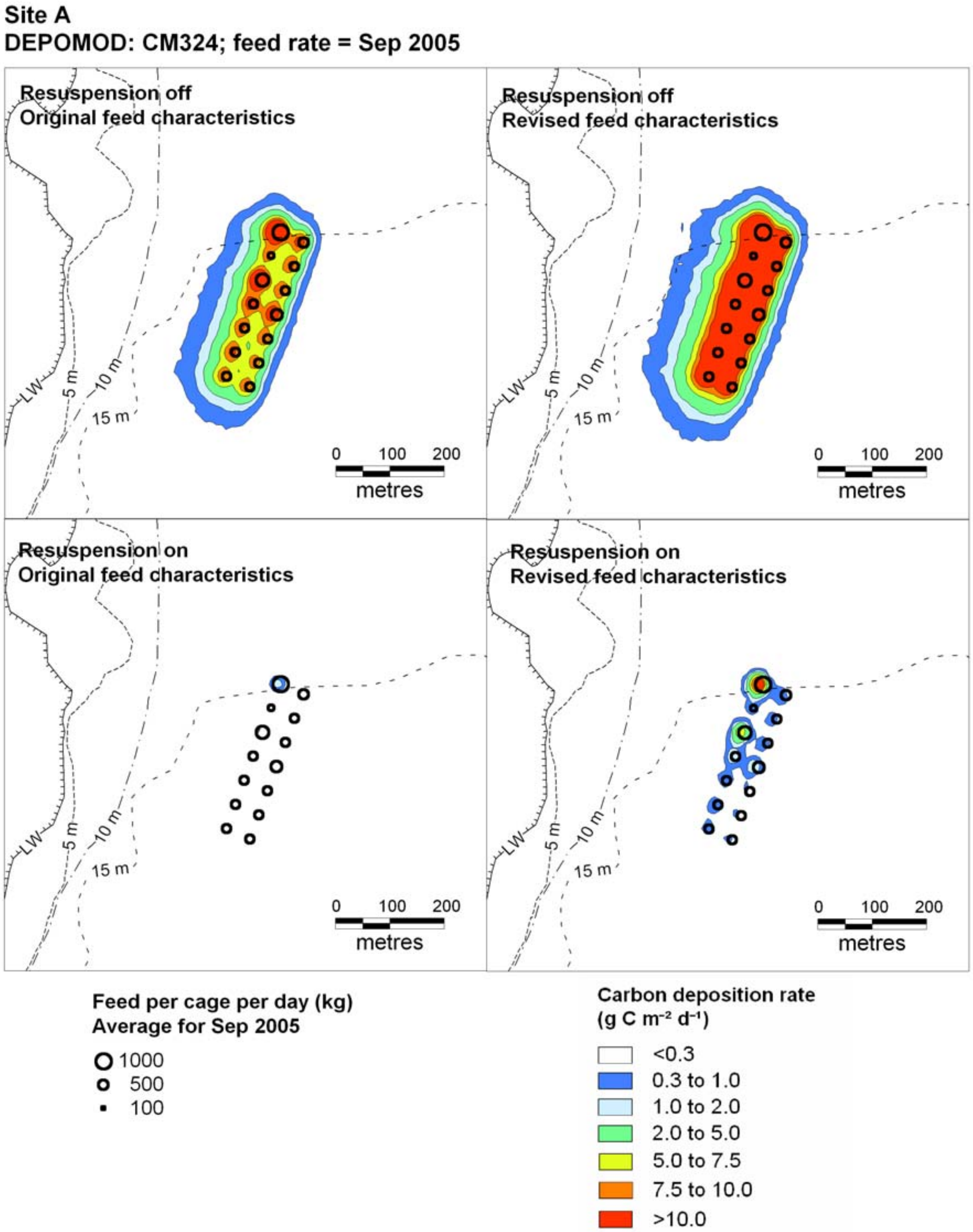


Fig. D1. Contour plots of DEPOMOD predicted carbon deposition rates at site A in September 2005 with current velocity data from meter deployment CM324, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005.

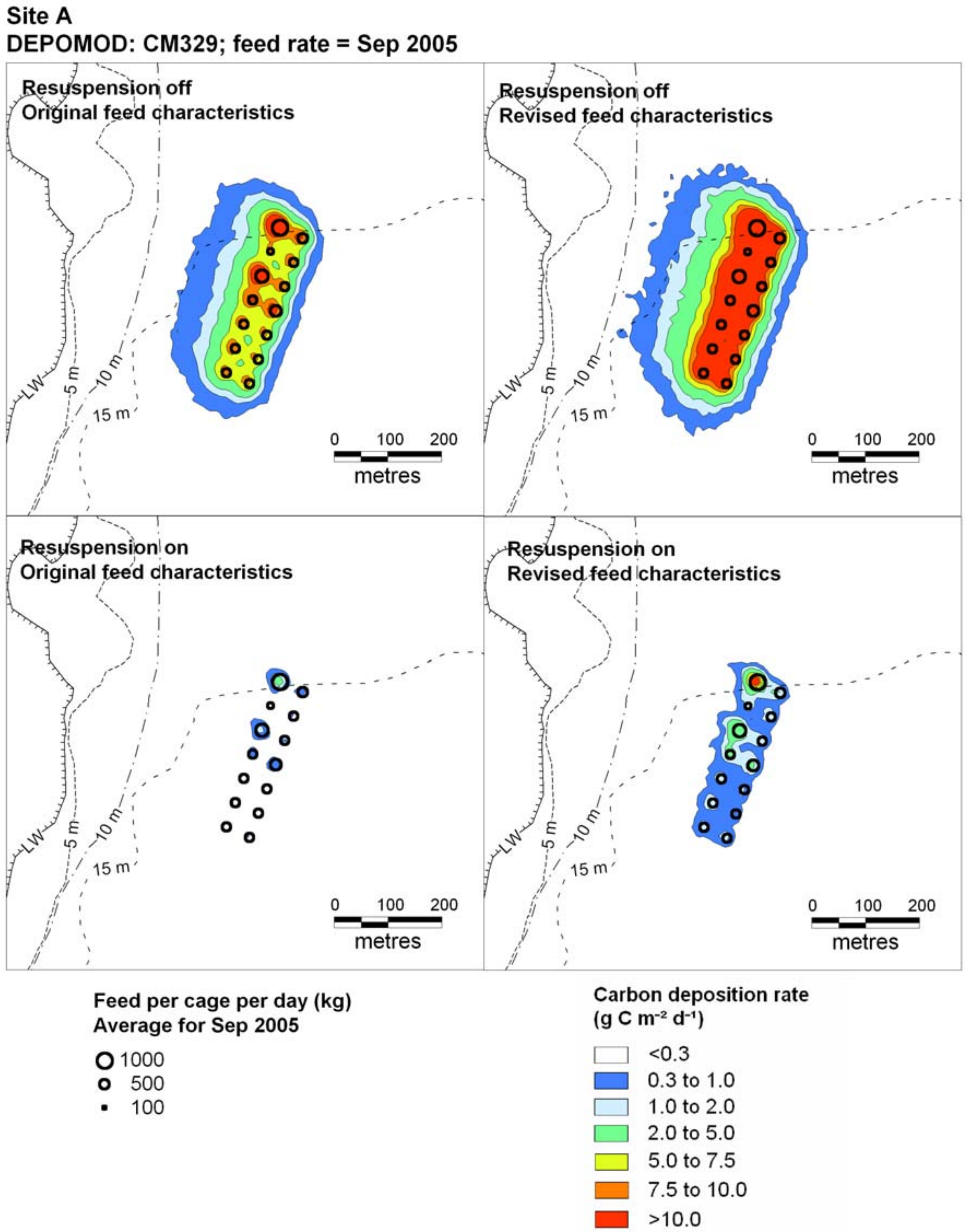


Fig. D2. Contour plots of DEPOMOD predicted carbon deposition rates at site A in September 2005 with current velocity data from meter deployment CM329, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005.

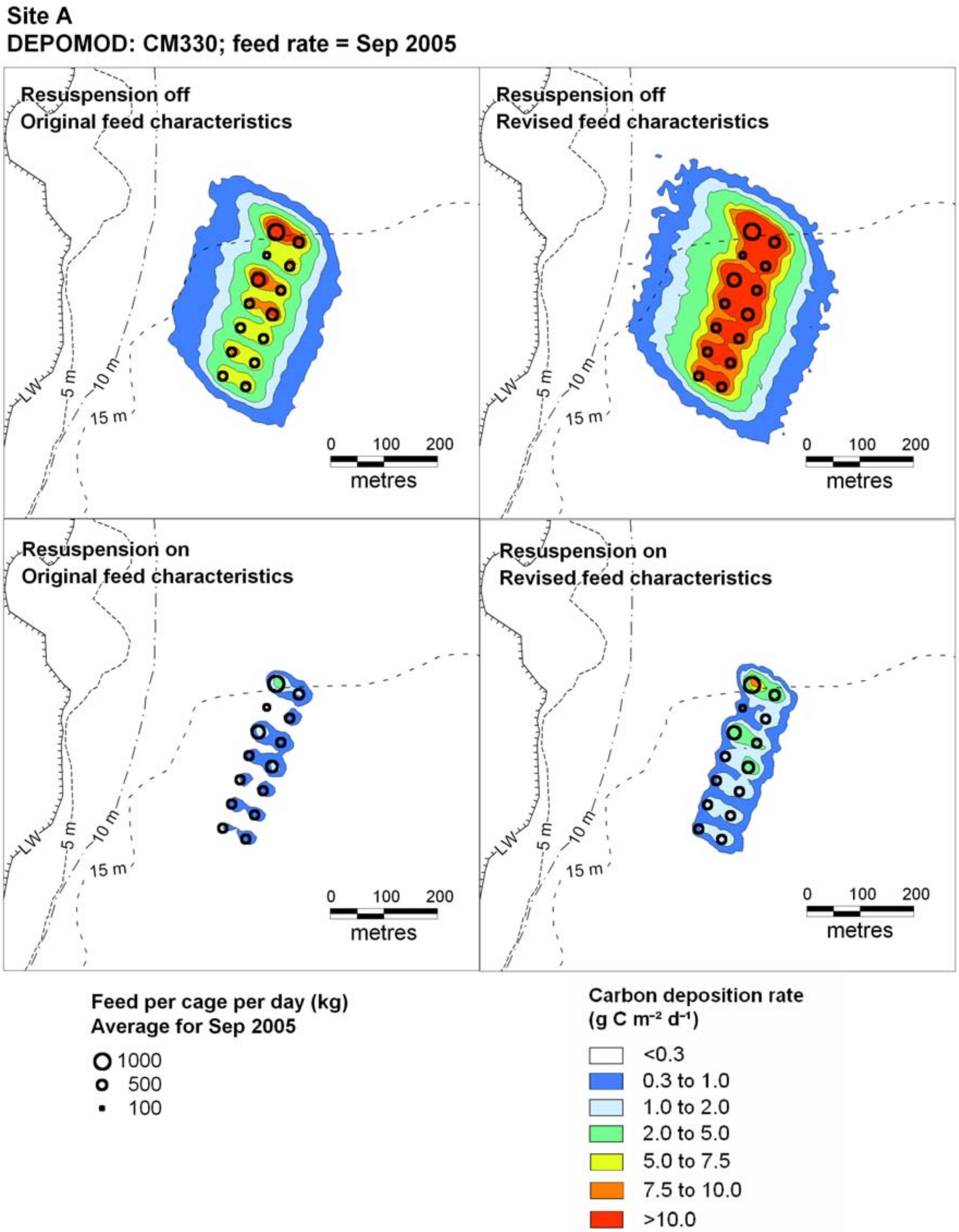


Fig. D3. Contour plots of DEPOMOD predicted carbon deposition rates at site A in September 2005 with current velocity data from meter deployment CM330, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2005.

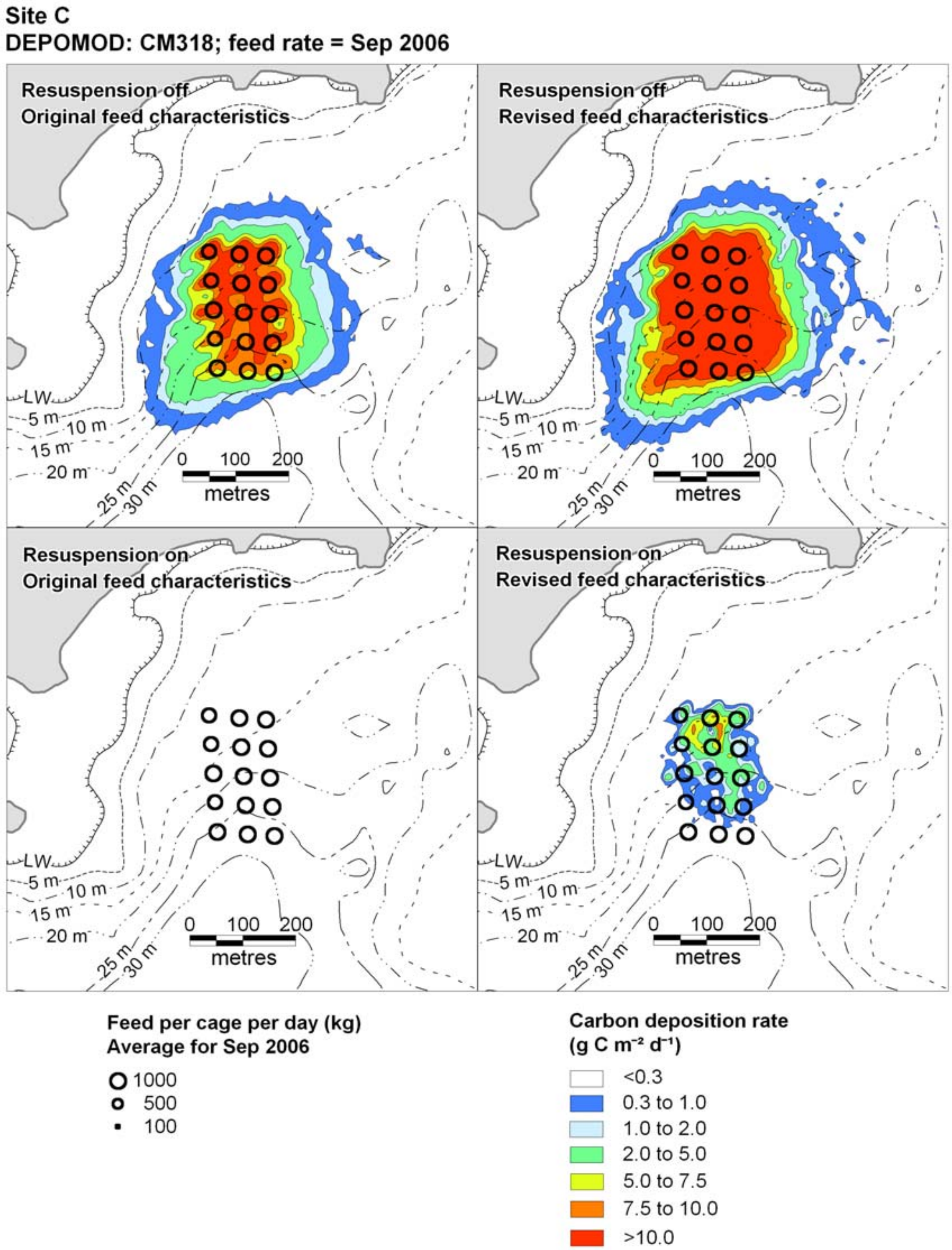


Fig. D4. Contour plots of DEPOMOD predicted carbon deposition rates at site C with current velocity data from meter deployment CM318, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2006.

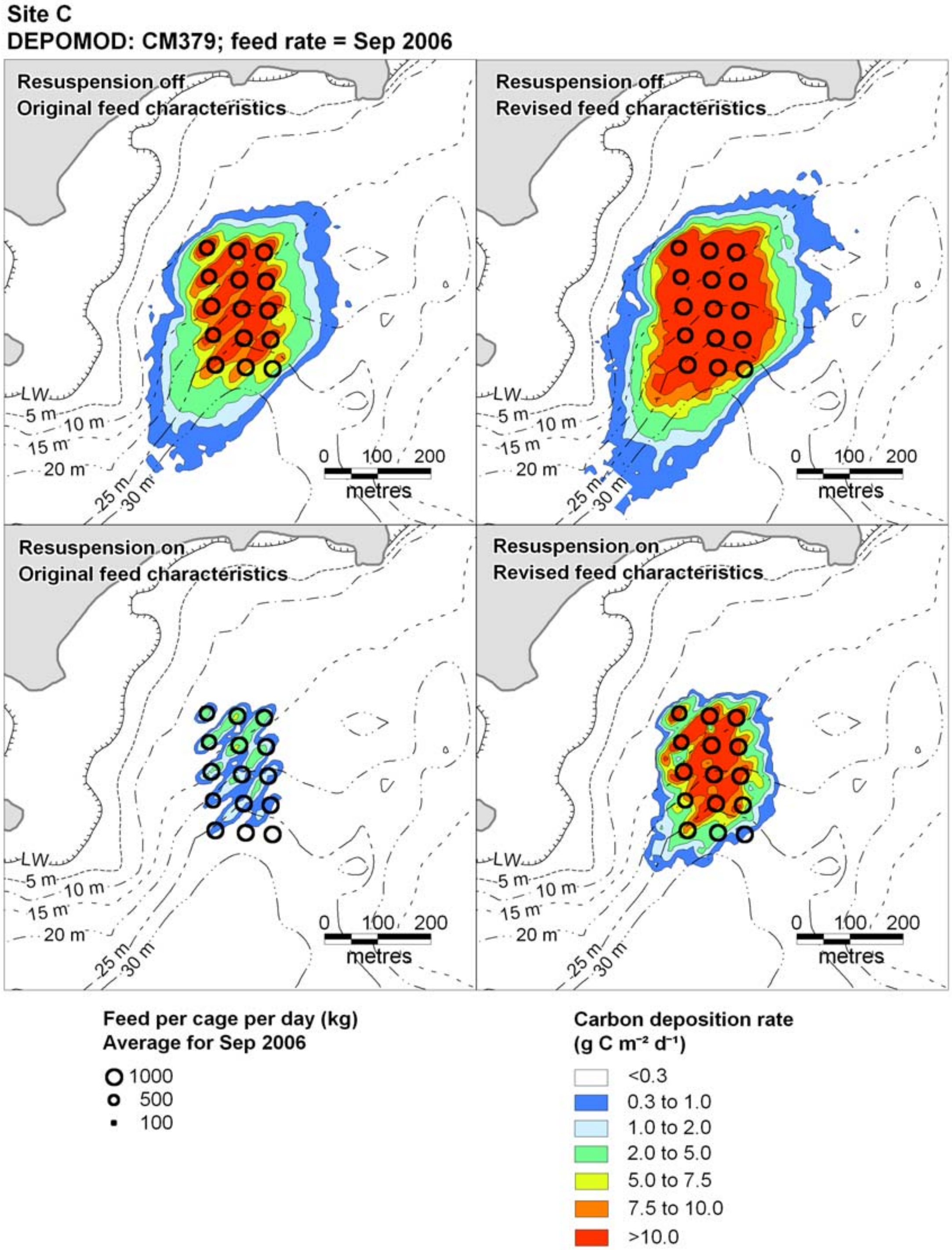


Fig. D5. Contour plots of DEPOMOD predicted carbon deposition rates at site C with current velocity data from meter deployment CM379, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during September 2006.

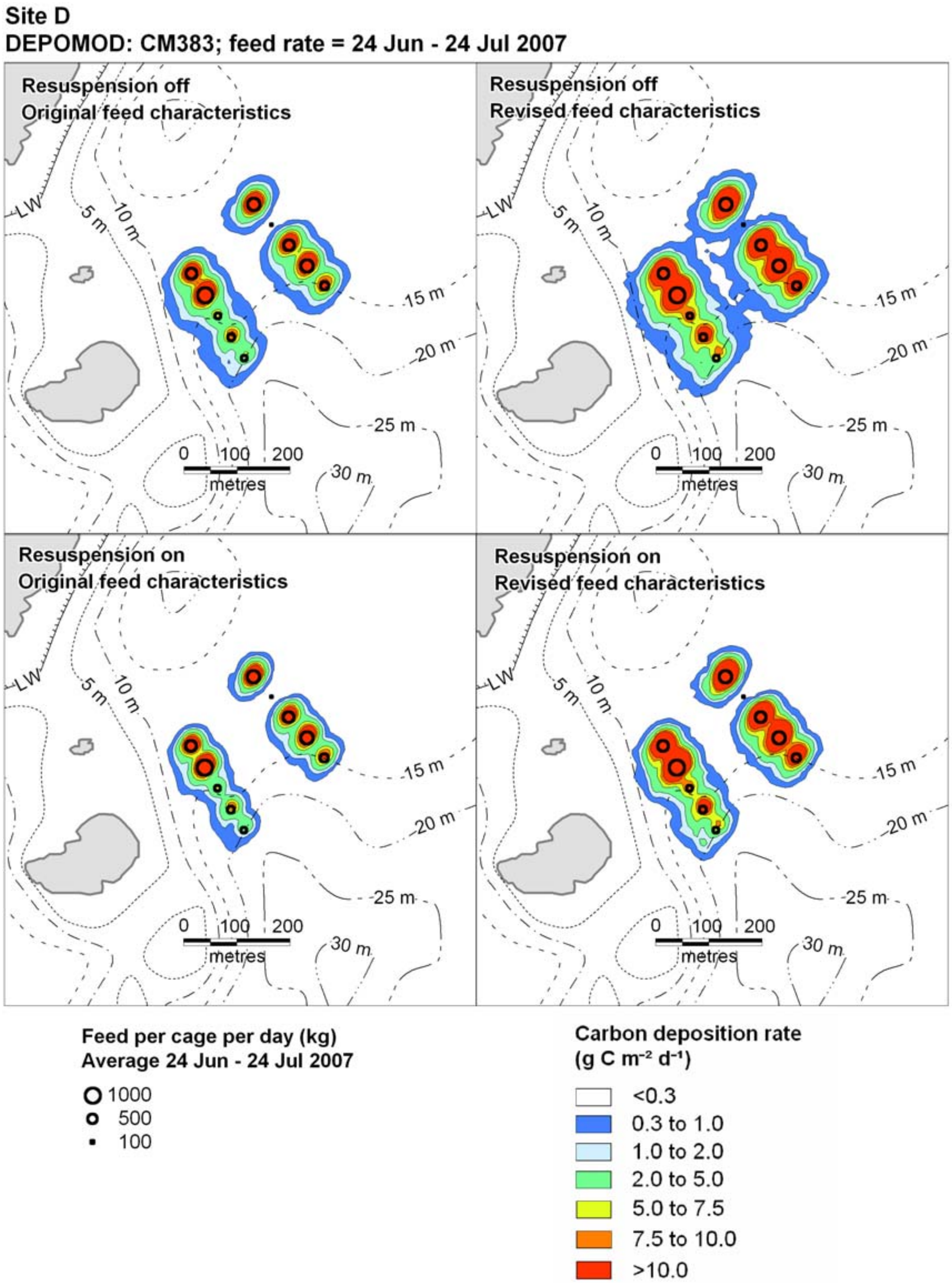


Fig. D6. Contour plots of DEPOMOD predicted carbon deposition rates at site D with current velocity data from meter deployment CM383, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 24 June–24 July 2007.

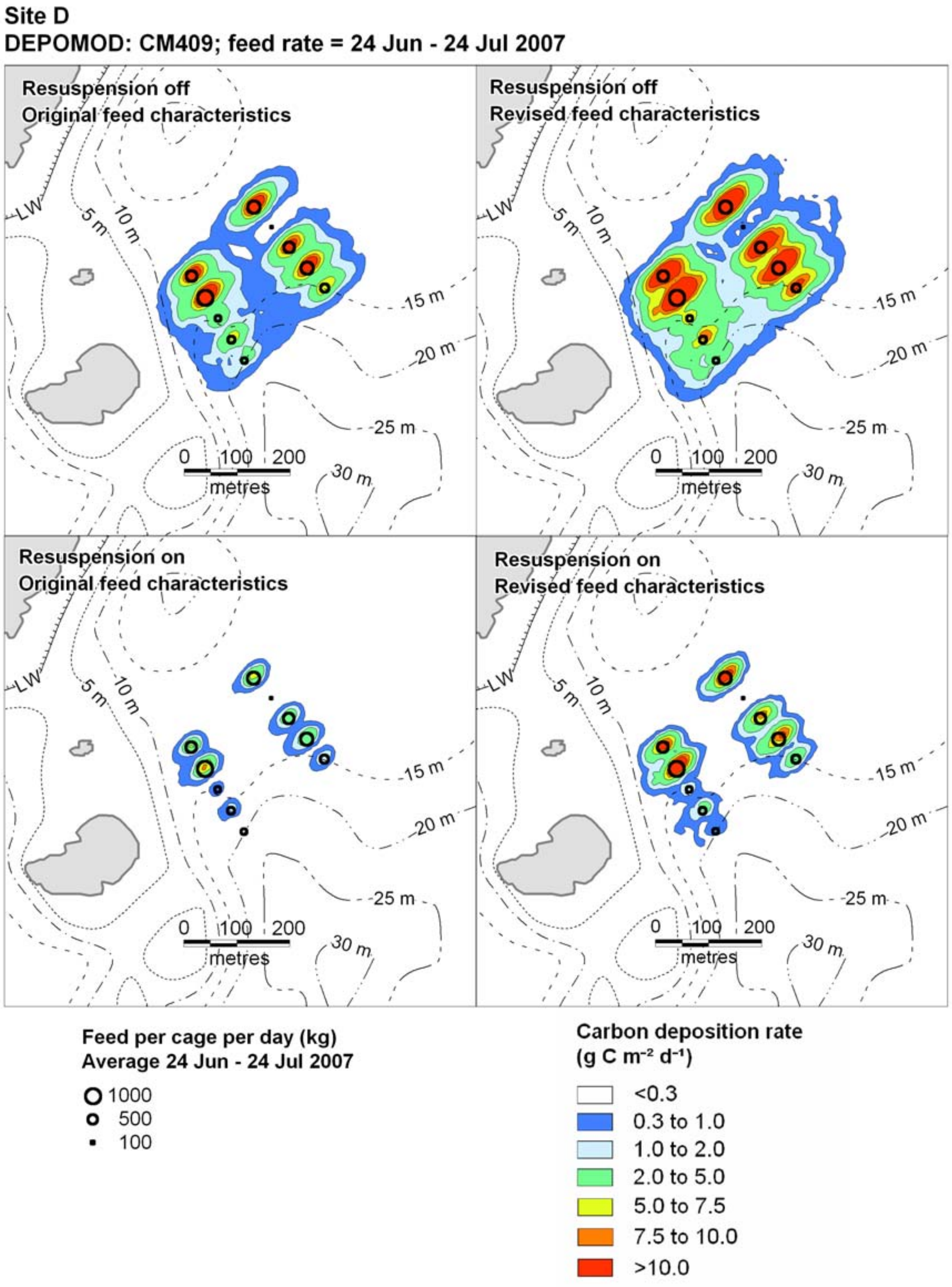


Fig. D7. Contour plots of DEPOMOD predicted carbon deposition rates at site D with current velocity data from meter deployment CM409, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 24 June–24 July 2007.

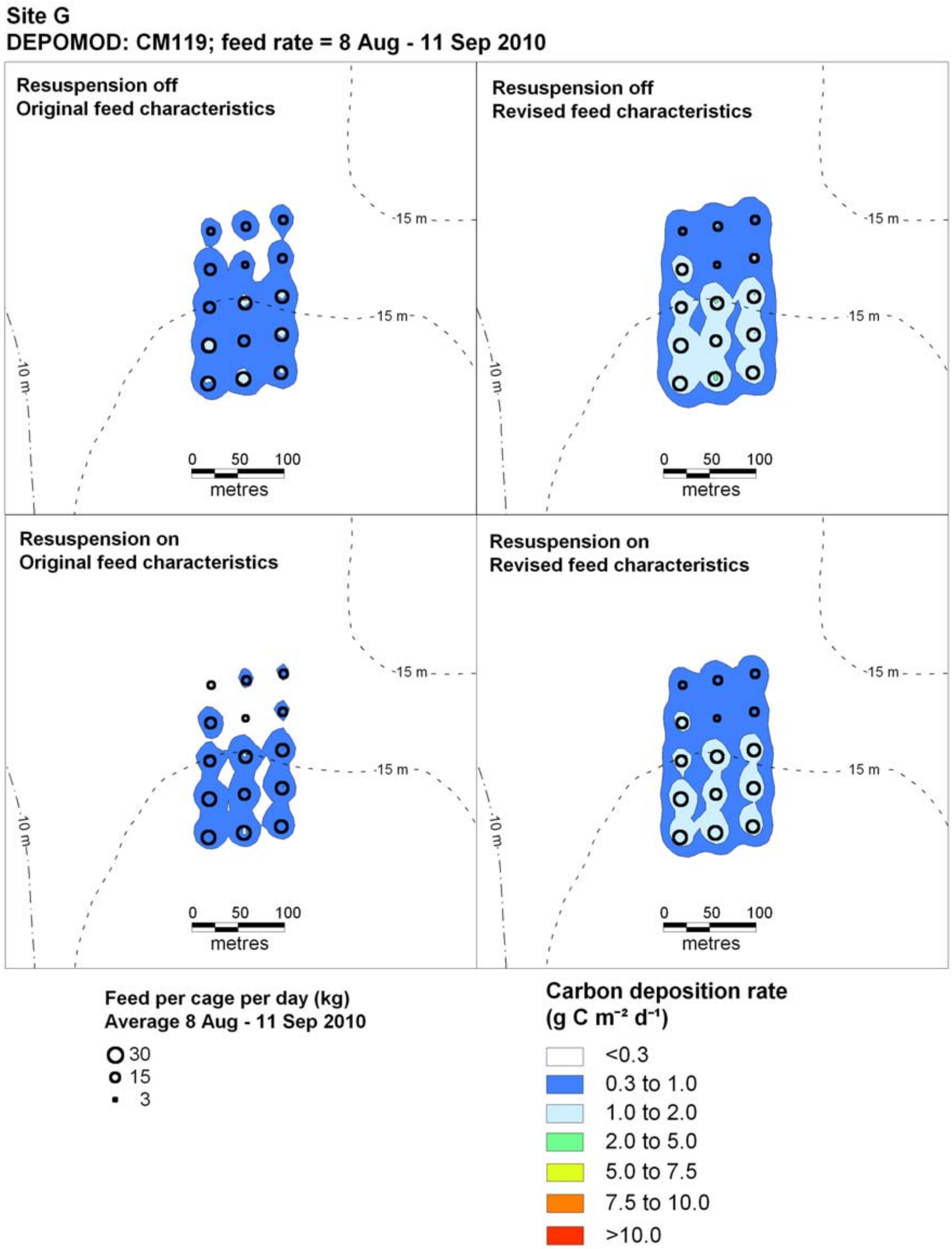


Fig. D8. Contour plots of DEPOMOD predicted carbon deposition rates at site G with current velocity data from meter deployment CM119, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 8 August–11 September 2010.

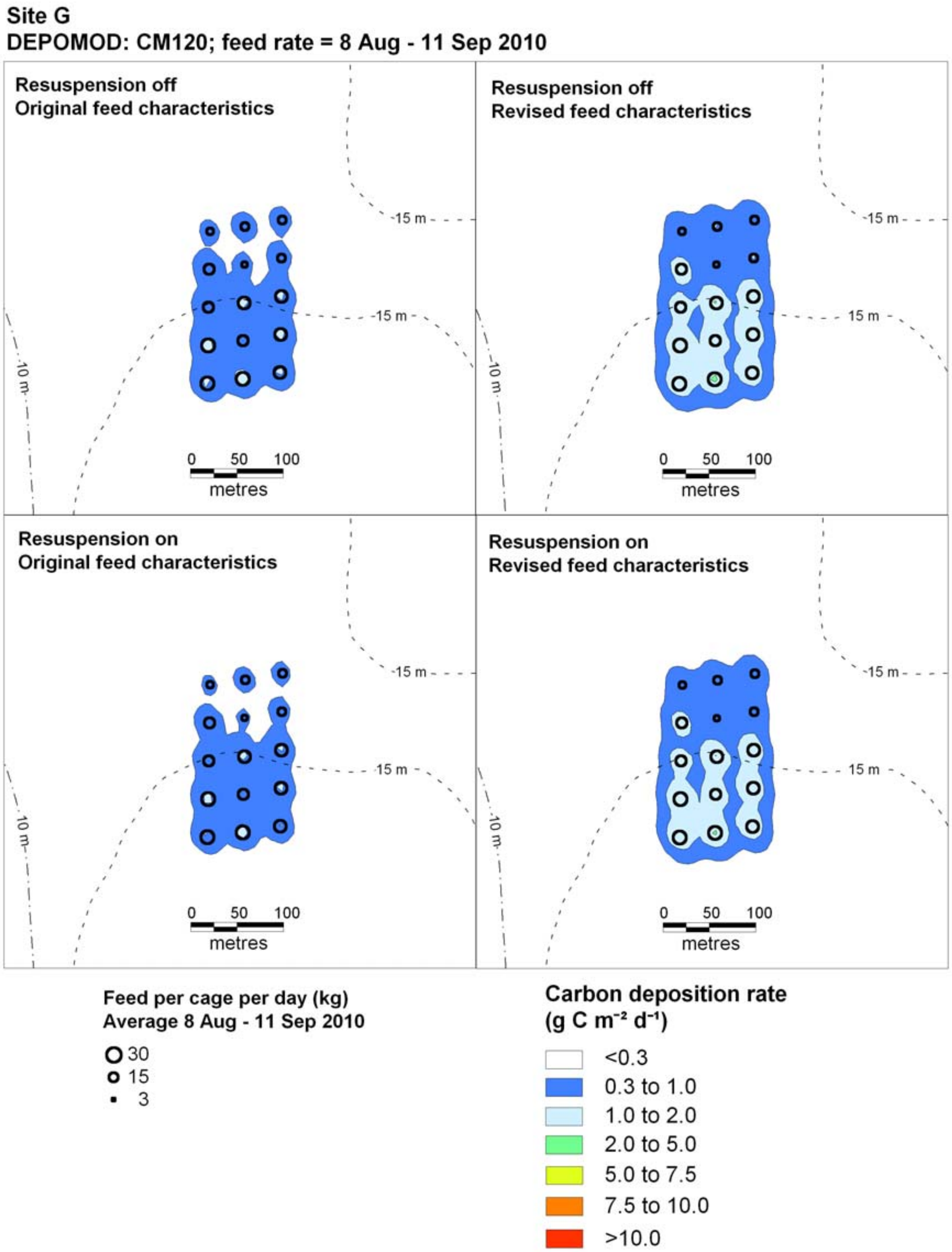


Fig. D9. Contour plots of DEPOMOD predicted carbon deposition rates at site G with current velocity data from meter deployment CM120, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 8 August–11 September 2010.

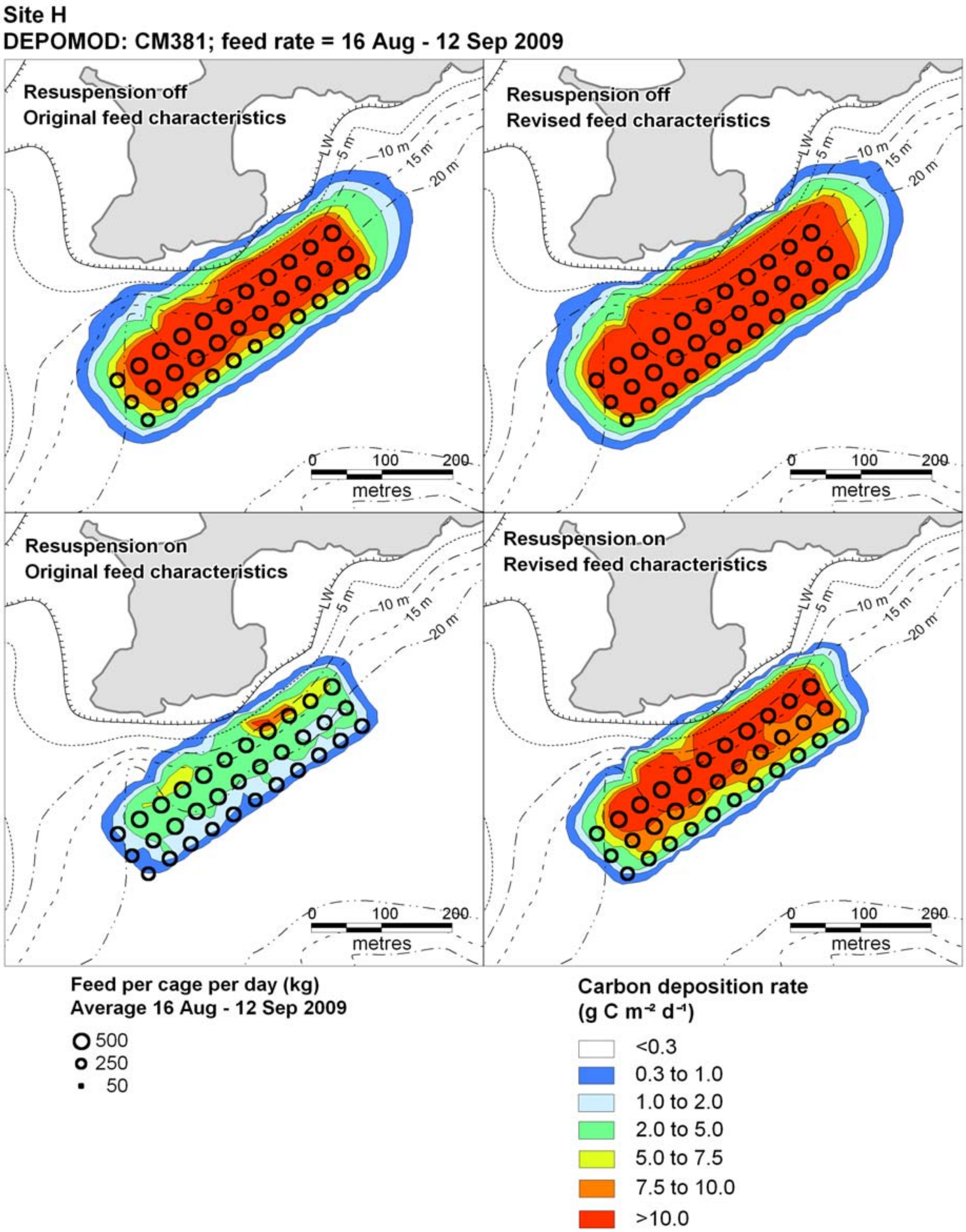


Fig. D10. Contour plots of DEPOMOD predicted carbon deposition rates at site H with current velocity data from meter deployment CM381, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 16 August–12 September 2009.

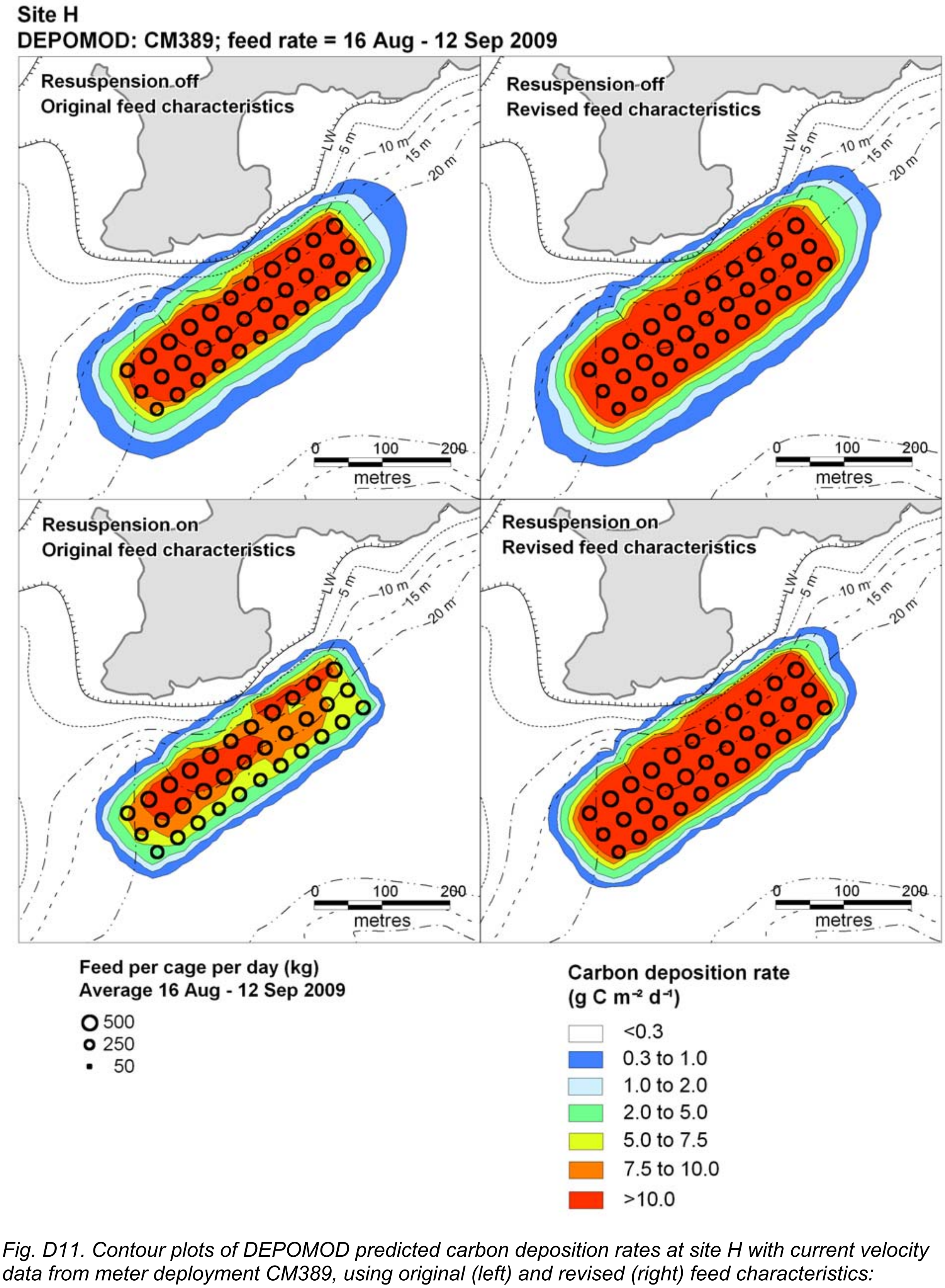


Fig. D11. Contour plots of DEPOMOD predicted carbon deposition rates at site H with current velocity data from meter deployment CM389, using original (left) and revised (right) feed characteristics: resuspension off (top) and resuspension on (bottom). Circles indicate approximate cage locations, with circle sizes representing the average feed rate per day in each cage during 16 August–12 September 2009.

Appendix E. Comparison of Contour Plots of DEPOMOD Outputs using Three Grid Interpolation Techniques

Comparisons of contour plots of DEPOMOD predicted carbon deposition rates were made using three grid interpolation techniques within MapInfo Vertical Mapper (v.3.1.1). Comparisons were made for DEPOMOD predictions using one set of current velocity data per site and feed rates at the time of summer-fall sediment sampling. The contour intervals were defined by the carbon deposition rates corresponding to the sediment classifications, as in Table 1 of the main report.

For evenly spaced data, such as DEPOMOD outputs, the contouring software recommends three possible grid interpolation techniques: rectangular, natural neighbor, and kriging (MapInfo Corporation 2005).

Rectangular interpolation can only be used when data is evenly distributed (as in DEPOMOD outputs). The interpolation surface passes through all points, without overshooting maximum values or undershooting minimum values. This interpolation technique was used for all contour plots of DEPOMOD data in the main report. Default values (calculated by the contouring software) for Cell size and Search radius were used.

Natural Neighbor interpolation uses area-weighting to determine new values for each grid node. The Simple method option within natural neighbor interpolation was used. Default values (calculated by Vertical Mapper) were used for Cell size and Aggregation distance. The default Surface Solution Type was used: Smoothed, without overshoot.

Kriging considers both the distance and the degree of variation between known data points. The Universal kriging method (using default values) and the punctual form (the default option) were used.

The differences in the contour areas produced by the three techniques were relatively small (Table E1). The predicted areas where the carbon deposition rate was >5 g C m^{-2} d^{-1} ranged from 26,300 – 26,700 m^2 at site A; 49,800 – 50,200 m^2 at site C; 12,500 – 14,600 m^2 at site D; 0 m^2 using all three techniques at site G; and 48,300 – 50,900 m^2 at site H.

The contour maps produced using the three interpolation techniques were similar (Fig. E1-E5). The geographic distributions of elevated deposition rates were similar for each site, except that the maps produced using the kriging technique were less smoothed.

Reference

MapInfo Corporation. 2005. Vertical Mapper version 3.0 user guide. MapInfo Corporation. Troy, NY, USA.

Table E1. Estimated areas of seafloor within EMP classifications, based on DEPOMOD predictions of carbon deposition rates, with resuspension off, using three grid interpolation techniques in MapInfo Vertical Mapper (v.3.1.1): rectangular, natural neighbor (simple), and kriging (universal, punctual).

Site classification	Carbon deposition rate ($g\ C\ m^{-2}\ d^{-1}$)	Contour area (m^2)		
		Rectangular	Natural Neighbor (simple)	Kriging (universal, punctual)
Site A: CM324 (Feed rate Sep 2005)				
Oxic A	0.3-1.0	21,600	21,600	21,600
Oxic B	1.0-2.0	10,500	10,400	11,000
Hypoxic A	2.0-5.0	12,300	12,400	12,900
Hypoxic B	5.0-7.5	13,800	13,200	12,300
Hypoxic C	7.5-10.0	8,900	8,600	9,200
Anoxic	>10.0	4,000	4,500	5,200
>5 $g\ C\ m^{-2}\ d^{-1}$	>5.0	26,700	26,300	26,700
Site C: CM318 (Feed rate Sep 2006)				
Oxic A	0.3-1.0	35,800	35,700	35,800
Oxic B	1.0-2.0	18,000	17,900	18,300
Hypoxic A	2.0-5.0	28,500	28,700	29,000
Hypoxic B	5.0-7.5	13,000	13,100	13,800
Hypoxic C	7.5-10.0	16,500	16,100	15,600
Anoxic	>10.0	20,700	20,600	20,500
>5 $g\ C\ m^{-2}\ d^{-1}$	>5.0	50,200	49,800	49,900
Site D: CM383 (Feed rate 24 Jun – 24 Jul 2007)				
Oxic A	0.3-1.0	21,100	21,100	22,200
Oxic B	1.0-2.0	10,900	10,900	11,100
Hypoxic A	2.0-5.0	13,800	13,400	13,300
Hypoxic B	5.0-7.5	4,500	4,400	5,500
Hypoxic C	7.5-10.0	2,800	2,500	2,700
Anoxic	>10.0	5,400	5,600	6,400
>5 $g\ C\ m^{-2}\ d^{-1}$	>5.0	12,700	12,500	14,600
Site G: CM119 (Feed rate 8 Aug – 11 Sep 2010)				
Oxic A	0.3-1.0	17,300	16,700	17,400
Oxic B	1.0-2.0	600	1,100	1,300
Hypoxic A	2.0-5.0	0	0	0
Hypoxic B	5.0-7.5	0	0	0
Hypoxic C	7.5-10.0	0	0	0
Anoxic	>10.0	0	0	0
>5 $g\ C\ m^{-2}\ d^{-1}$	>5.0	0	0	0
Site H: CM381 (Feed rate 16 Aug – 12 Sep 2009)				
Oxic A	0.3-1.0	16,400	15,000	18,000
Oxic B	1.0-2.0	10,800	10,100	11,700
Hypoxic A	2.0-5.0	15,500	14,800	19,000
Hypoxic B	5.0-7.5	8,000	7,300	10,800
Hypoxic C	7.5-10.0	8,400	8,300	10,000
Anoxic	>10.0	32,400	32,700	30,100
>5 $g\ C\ m^{-2}\ d^{-1}$	>5.0	48,800	48,300	50,900

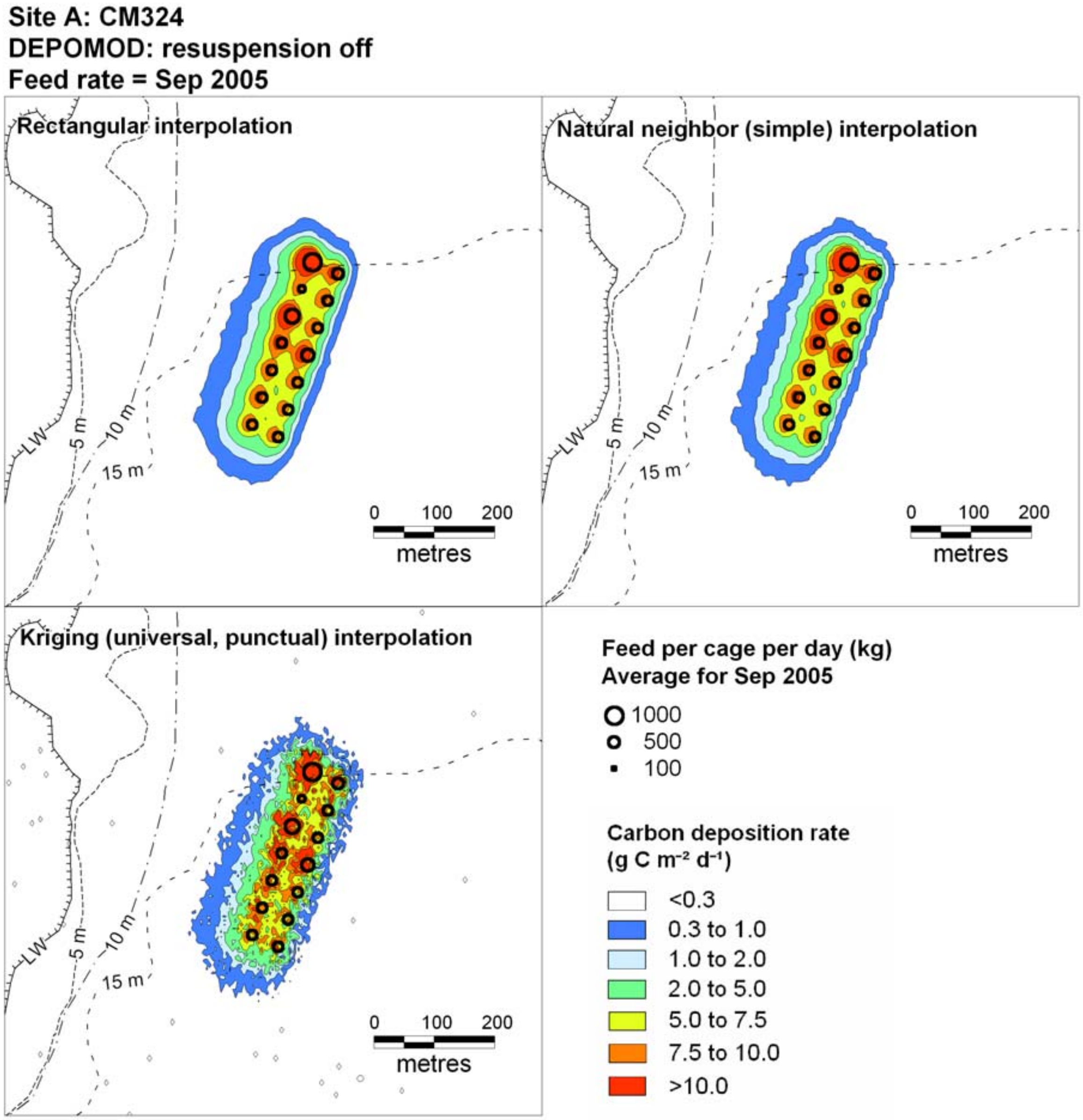


Fig. E1. Contour plots of DEPOMOD predicted carbon deposition rates at site A (resuspension off), using three interpolation techniques in MapInfo Vertical Mapper (v.3.1.1): rectangular, natural neighbor (simple), and kriging (universal, punctual).

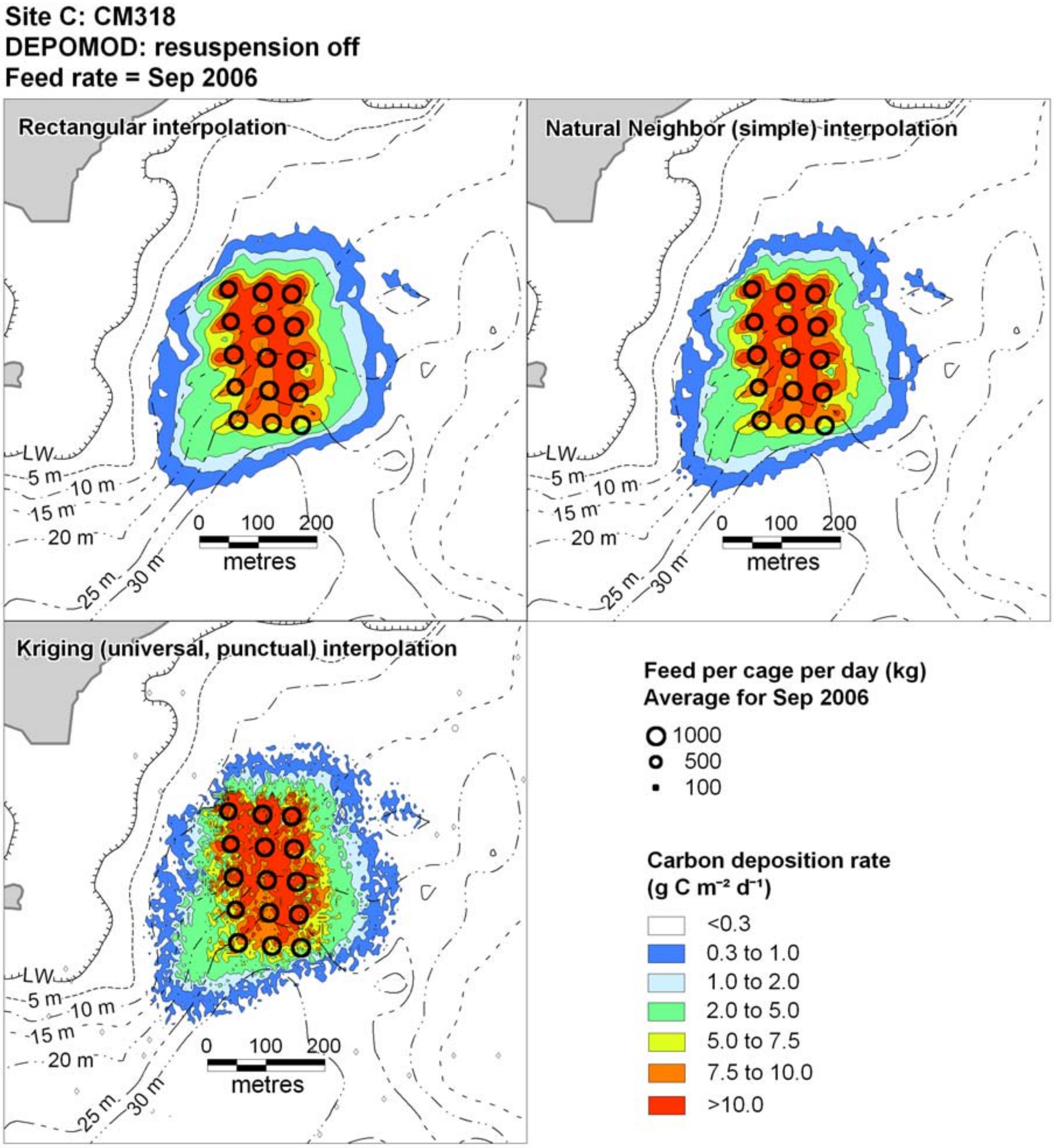


Fig. E2. Contour plots of DEPOMOD predicted carbon deposition rates at site C (resuspension off), using three interpolation techniques in MapInfo Vertical Mapper (v.3.1.1): rectangular, natural neighbor (simple), and kriging (universal, punctual).

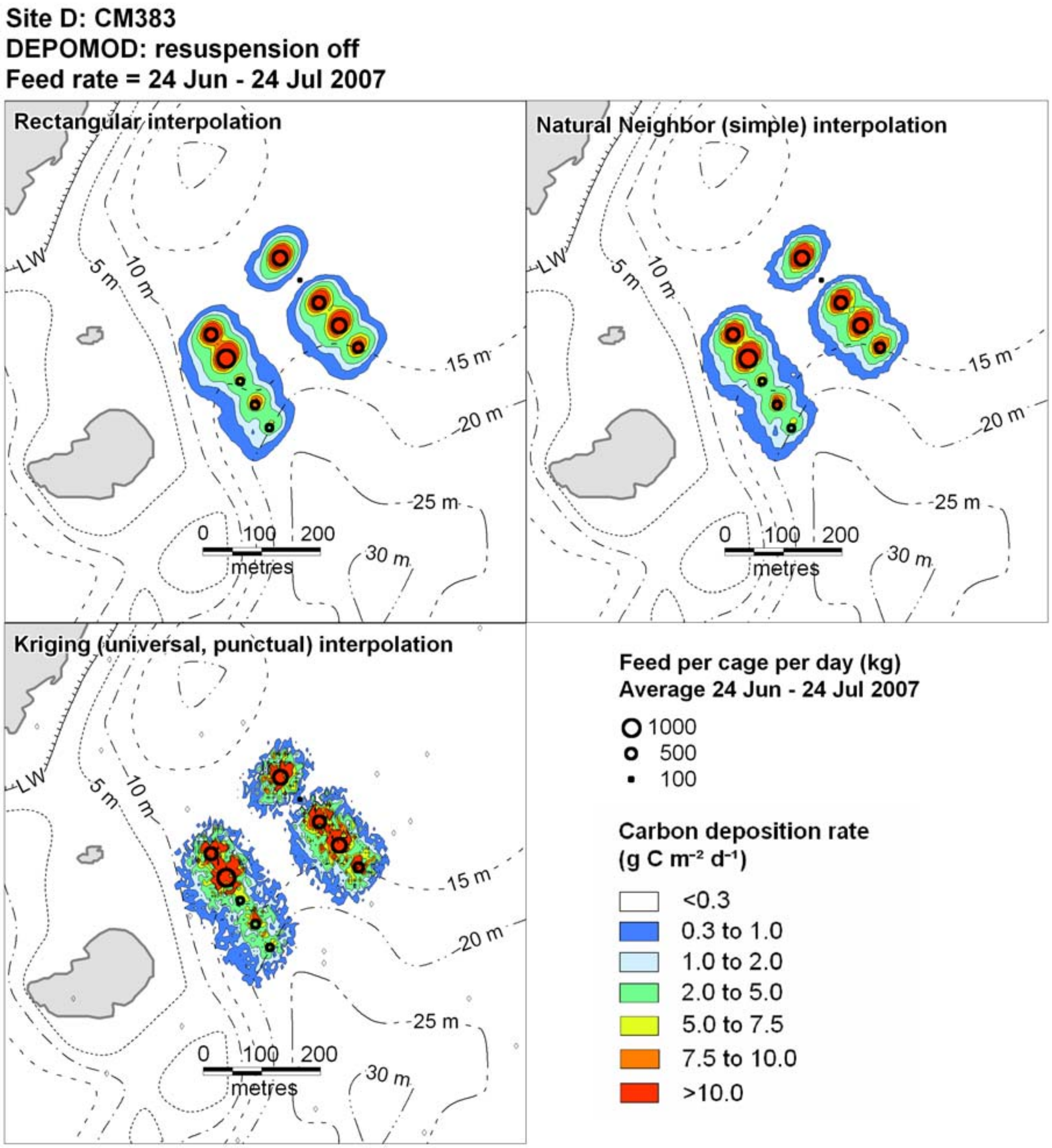


Fig. E3. Contour plots of DEPOMOD predicted carbon deposition rates at site D (resuspension off), using three interpolation techniques in MapInfo Vertical Mapper (v.3.1.1): rectangular, natural neighbor (simple), and kriging (universal, punctual).

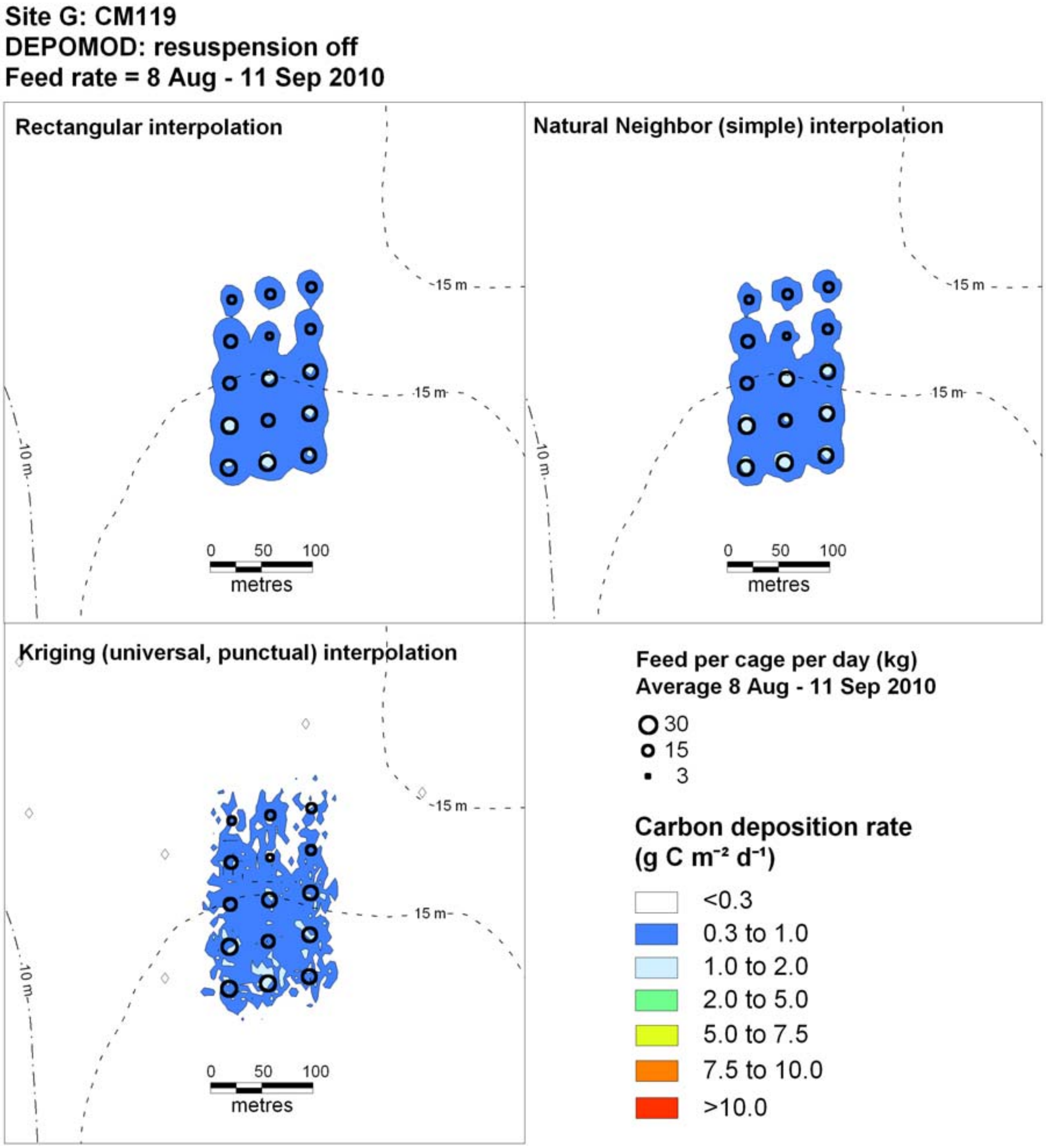


Fig. E4. Contour plots of DEPOMOD predicted carbon deposition rates at site G (resuspension off), using three interpolation techniques in MapInfo Vertical Mapper (v.3.1.1): rectangular, natural neighbor (simple), and kriging (universal, punctual).

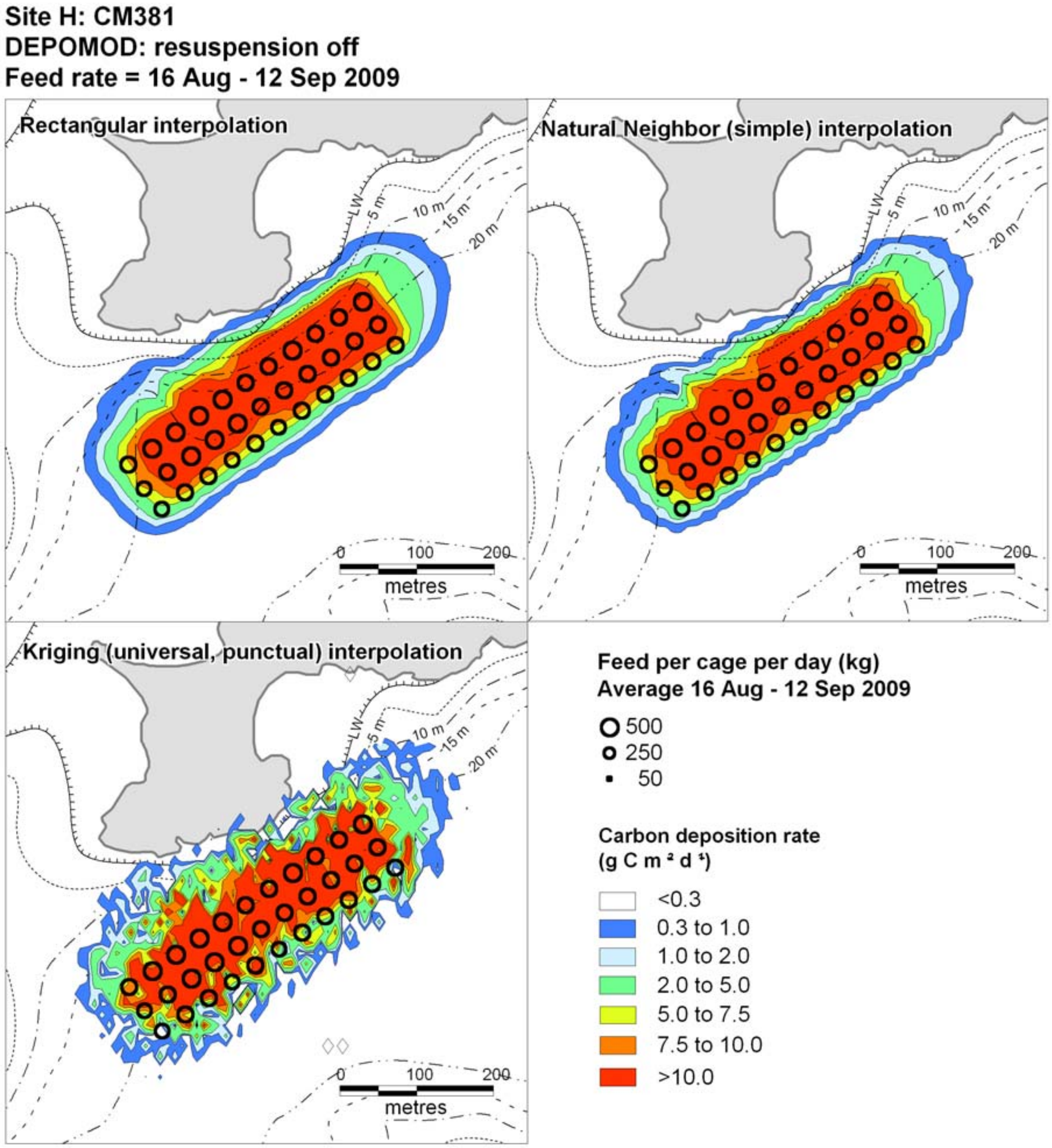


Fig. E5. Contour plots of DEPOMOD predicted carbon deposition rates at site H (resuspension off), using three interpolation techniques in MapInfo Vertical Mapper (v.3.1.1): rectangular, natural neighbor (simple), and kriging (universal, punctual).