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The Effects of the Endicott Development Project on the Boulder Patch, an Arctic Kelp Community in Stefansson Sound, Alaska

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ABSTRACT. The Boulder Patch in Stefansson Sound, Beaufort Sea, of Alaska harbors a diverse arctic kelp community in areas where rock cover exceeds 10%. In 1985, the Endicott Development Project, the first major offshore oil development in the Alaskan Arctic, was constructed shoreward of this community at the mouth of the Sagavanirktok River. A 7-year study was conducted to determine the effects of the development on kelp health and growth and taxa diversity of the overall community. No adverse effects were detected. The regional patterns of sediment transport served to protect the community from development-derived sediment loadings and discharges. Sediment transport patterns likely also contribute to the unusual presence of this community in the sound.

Key words: Boulder Patch, kelp, *Laminaria solidungula*, Beaufort Sea, productivity, colonization, epilithic community, epilithic flora, epilithic fauna, benthic community, sediment transport

RÉSUMÉ. Boulder Patch, dans le détroit Stefansson situé dans la mer de Beaufort (Alaska), abrite une communauté d'algues diversifiée dans les endroits où la couverture rocheuse dépasse 10 p. cent. En 1985 a été lancé le projet de développement d'Endicott, premier grand aménagement d'exploitation pétrolière en mer dans l'Arctique alaskien, établi entre le rivage et cette communauté, à l'embouchure de la rivière Sagavanirktok. Une étude de sept ans a été menée pour déterminer les effets du développement sur l'état de santé et la croissance des algues ainsi que sur la diversité des taxons de l'ensemble de la communauté. Aucun effet nocif n'a été détecté. Les schémas régionaux du transport sédimentaire ont servi à protéger la communauté de l'accumulation et du débit sédimentaires dus à l'exploitation. Les schémas de transport des sédiments ont aussi probablement contribué à la présence inhabituelle de cette communauté dans le détroit.

Mots clés: Boulder Patch, algues, *Laminaria solidungula*, mer de Beaufort, productivité, colonisation, communauté épilithique, flore épilithique, faune épilithique, communauté benthique, transport solide

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INTRODUCTION

In the early 1970s, researchers from the U.S. Geological Survey discovered anomalous areas within Stefansson Sound in the Beaufort Sea, Alaska (Fig. 1) where the characteristic mud bottom was covered by patches of rock (Reimnitz and Toimil, 1976). Stefansson Sound is a large barrier island-lagoon system off the Sagavanirktok River. The area of Stefansson Sound containing rocky substrate was charted (Fig. 2A) and designated as the "Boulder Patch" by the U.S. Board of Geographic Names. Although boulders up to 2 m across and 1 m high are sometimes encountered, most of the rock cover occurs in the pebble to cobble size range. The Boulder Patch is thought to be composed of rocks of Flaxman formation origin that were ice rafted to the area and incorporated in the Gubik formation at an earlier time (Dunton *et al.*, 1982).

Isolated patches of marine life were discovered in areas where the rocks were widely scattered (10-25% rock cover). However, in areas where the rock cover was dense (>25% bottom cover), the rocks harbored a rich epilithic flora and fauna, including extensive beds of the kelp *Laminaria solidungula*. While kelp communities are common in arctic waters outside of Alaska, this community was hundreds of kilometres disjunct from the main range (Fig. 1) and was totally unexpected. Since its discovery, the Boulder Patch has captivated the interest of scientists and resource agencies.

Dunton *et al.* (1982) described the structure and composition of the Boulder Patch community and the growth characteristics of *L. solidungula*. Dunton (1984) found that kelp production provides 50-56% of the carbon available to Boulder Patch consumers and that growth of *L. solidungula* is both energy and nitrogen limited because the two resources are not available in sufficient quantities simultaneously. During the summer open-water period, when light is available, the plants must fix all the carbon necessary for their annual growth, reproduction, and metabolism. However, little linear growth occurs during this period due to insufficient concentrations of inorganic nitrogen needed for synthesis of new tissue. The products of photosynthesis (carbohydrates in the form of laminarin or manitol) are stored and used during the winter, when inorganic nitrogen concentrations have increased to levels enabling growth of a new blade (Dunton and Schell, 1986). Consequently, *L. solidungula* often completes nearly 90% of its annual linear growth (mean 23 cm, range 22-25 cm) in darkness (Dunton *et al.*, 1982). However, when the ice canopy is clear, light reaches the plants during spring and annual growth increases significantly (Dunton, 1984).

L. solidungula has been found to thrive at low-light levels and is thus well adapted to the Arctic. It has the lowest irradiance saturation level (38 $\mu mol \cdot m^{-2} \cdot s^{-1}$) of any member of its genus and is photoinhibited at irradiance levels of 123 $\mu mol \cdot m^{-2} \cdot s^{-1}$ (Dunton and Jodwalis, 1988). Its compensation level (2.1 $\mu mol \cdot m^{-2} \cdot s^{-1}$; Dunton and Schonberg, 1990) is well below the levels of 5-9 $\mu mol \cdot m^{-2} \cdot s^{-1}$ for other congeneric species (Dunton and Schonberg, 1990). *L. solidungula* benefits from light increases up to 38 $\mu mol \cdot m^{-2} \cdot s^{-1}$, but no beneficial effect occurs above this level. Thus, years in which summer light levels are high do not necessarily relate to more than average annual growth. However, the plants benefit fully from any increases in light received during the winter-spring period because ambient

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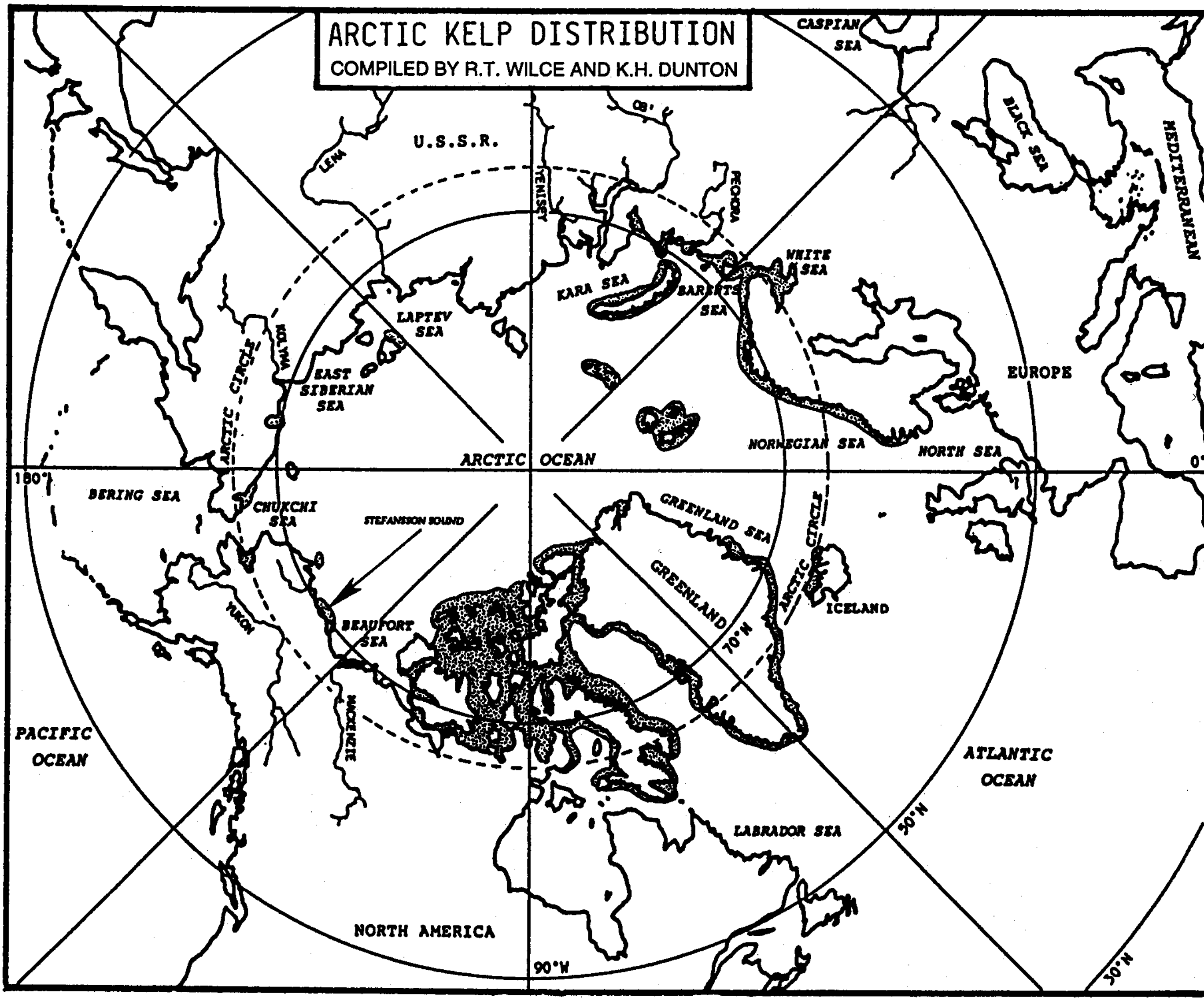

FIG. 1. Circumpolar distribution of arctic kelp bed communities, showing the Boulder Patch to be a small, disjunct community.

light levels are usually well below the saturation level (Dunton and Jodwalis, 1988).

Petroleum exploration from 1976 to 1980 resulted in the discovery of a large reservoir of oil and gas located offshore of the Sagavanirktok River delta near the Boulder Patch. In September 1982, BP Exploration (Alaska) Inc. (BPX) proposed to develop this reservoir using two drilling islands connected to each other and the mainland by solid-fill gravel causeways. The facility was collectively known as the Endicott Development Project (Fig. 2B). Although no structures were to be constructed in the Boulder Patch, there was concern that increased turbidity and sedimentation from the development might extend into the Boulder Patch and adversely affect the biological communities. The main concern was that ambient light might be reduced to levels that would impair the growth and health of the kelp.

These concerns were addressed in an environmental impact statement (EIS) (U.S. Army Corps of Engineers [USACE], 1984). Areas near the development having greater than 10% rock cover (and thus the potential for high-diversity biological communities) were delineated (Fig. 2B) based upon high-resolution benthic surveys (Toimil and England, 1980; Miller and England, 1982). Extensive physical and computer simulations were conducted under various discharge levels and meteorological conditions to estimate drilling mud plume trajectories and areas of bottom where increased sedimentation might occur from the development. The EIS concluded that some areas in the southern part of the Boulder Patch might experience periodic exposure to turbid water plumes and increased sedimentation under some extreme conditions. These events were not expected to have significant adverse effects on the community because of their low frequency and short duration (USACE, 1984).

In the summer of 1984, BPX independently initiated a pre-construction study to gather data that could be used to evaluate the effects of the development on the Boulder Patch (Dunton *et al.*, 1985). This study was followed by a 6-year monitoring program (1986-91) yielding 5 years of synoptic light and kelp growth data and 6 years of community diversity data (Gallaway and Martin, 1987; Gallaway *et al.*, 1988;

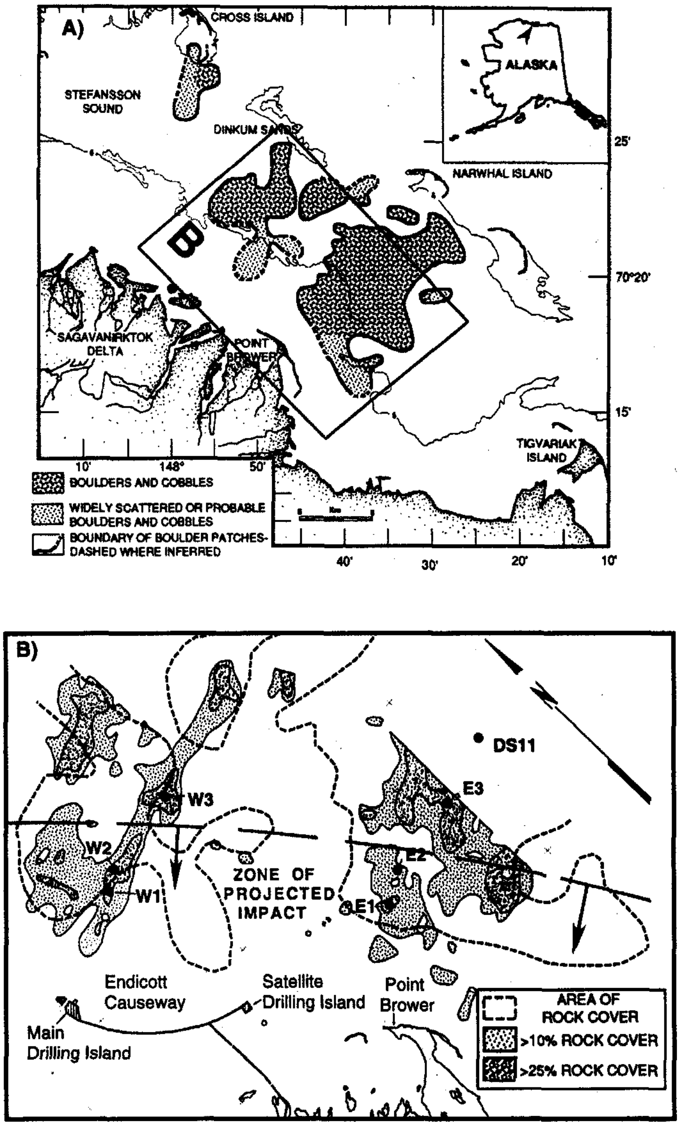

FIG. 2. (A) shows the distribution of rock cover in Stefansson Sound (as mapped by Reimnitz and Ross, 1979) that was formally designated as the Boulder Patch by the United States Board of Geographic Names. (B) shows the actual distribution of rock cover > 10 and 25% relative to the original surveys. (B) also shows the location of our sampling sites and the boundary within which impacts from the Endicott Development were projected to be restricted. Sites DS-11, E-3, and W-3 served as controls for stations E-1, E-2, W-1, and W-2.

LGL Ecological Research Associates, Inc. [LGL] and Dunton, 1989, 1990, 1991, 1992). This paper provides a synthesis of these studies and evaluates the effects of the development on Boulder Patch biological communities.

STUDY AREA AND METHODS

Study Area

Seven sites with rich biological communities were sampled in the baseline and monitoring programs (Fig. 2B). Four of these (E-1, E-2, W-1, and W-2) were designated "impact" sites because they were in or near areas that the EIS had predicted would be subjected to drilling mud plumes and increased sedimentation from the development under some extreme conditions. Sites W-3, E-3, and DS-11 were outside the area of any predicted effects from the development and were therefore taken to represent "control" sites. DS-11, the farthest sampling site from the development, has a longer history of kelp growth sampling than the other sites.

The control sites were characterized by 20% or greater rock cover (>50% at W-3, >20% at E-3, and >25% at DS-11). At the impact sites, rock cover at W-1 and W-2 was less than 20% and at E-1 and E-2 less than 15% (Dunton *et al.*, 1985). In 1984, sediment grain size also differed among the locations (Dunton *et al.*, 1985). Bottom sediments at the control sites were predominantly sand sized (especially W-3 and DS-11) or silty-sand mixtures (E-3). The impact sites E-1 and E-2 were characterized by various mixtures of sand-silt-clay, trending towards sand-sized particles. This contrasted with silty-clay sediments at impact sites W-1 and W-2. These baseline data suggested that the areas surrounding W-1 and W-2 were more depositional than the other sites prior to the development. Further, sediments at sites W-1 and W-2 would be more easily suspended because of their small grain size. This could lead to chronic reductions in water transparency at these sites.

Water depth at impact sites E-1 and E-2 was less (4.0 and 4.3 m respectively) than at sites W-1 and W-2 (5.1 and 5.5 m respectively). Water depth at control sites E-3 and DS-11 was also 5.5 m, and it was 6.1 m at W-3.

Annual Field Sampling

During each summer of the study, photosynthetically active radiation (ca 400-700 nm wavelength) at the survey sites was measured as photon flux fluence rates (PFFR, $\mu mol \cdot m^{-2} \cdot s^{-1}$, a measure of light reaching the bottom on a time and area basis). During 1984, synoptic irradiance data were gathered at sites E-1, W-1, and DS-11 during the period 11-18 August, but the duration of the sampling was not considered adequate for the data to be used as representative in the annual comparisons of summer irradiance data. In 1986-91, continuous irradiance data were gathered at all seven underwater sites and at one shore site throughout each year (Dunton and Jodwalis, 1988; Dunton, 1990). These data were used to evaluate the growth of kelp and associated effects of suspended sediment concentrations.

L. solidungula plants were collected each year at the seven sampling sites and analyzed for linear growth, tissue density, and carbon content, following the methods of Dunton (1984) and Dunton and Schell (1986). Linear growth of kelp reflects the quality of the environment during a growth year, whereas carbon content and tissue density reflect the immediate health or the growth potential of the plant for the next growth year. Tissue density and carbon content provide an index of the level of stored carbohydrates that can be mobilized for growth during the dark winter period.

In 1984, the growth measurements were made from 25 to 55 randomly collected plants at each site. In 1986, 20 plants were collected, tagged, and placed adjacent to the underwater light meters at each site where growth was monitored in following years. Lost plants were replaced from nearby areas as necessary to maintain sample size of about 20 plants. Tissue samples were obtained annually from 7 to 8 plants randomly collected near the light meters to determine tissue density and carbon content.

In 1984, 10 cobbles or boulders were marked and photographed at each of the seven underwater sites. Also, two bare Flaxman boulders obtained from shore were placed at sites DS-11, W-1, and E-1 to measure colonization rates. During 1986-91, the sample rocks at each site were relocated, if possible, and photographed. Changes in the epilithic community among years and sites were evaluated using the community summary statistics of taxa diversity, evenness, and richness, supplemented by graphs of observed changes in community structure.

The Shannon-Wiener diversity index (H″; Pielou, 1966a) was used to provide a quantitative index of the number of taxa represented and their relative proportions at each site within the study area. Differences in the index among sites indicate differences among communities, whereas differences in the index within sites over time indicate changes within the communities. Indices of richness (D; Dahlberg and Odum, 1970) and evenness (J; Pielou, 1966b) contribute additional information to help illustrate the nature of community changes.

Assessment Approach

Effects of the development on the Boulder Patch were evaluated using the BACI (Before After Control-Impact) model (Stewart-Oaten *et al.*, 1986). In this design, impact and control sites are sampled "simultaneously" at times before and after a development. Measurements taken over time represent true replicates, enabling statistical analysis (Stewart-Oaten *et al.*, 1986). Changes in the difference between control and impact sites "after" the development as compared to the "before" period reflect effects attributable to development.

In our application, the mean of the annual differences between control and impact sites for before and after periods were calculated along with the 95% confidence interval for each mean (±2SE). Differences between means were determined by inspection — i.e., the differences were considered significant at the 5% level when the confidence intervals did not overlap. The data were not amenable to more formal statistical analysis. A weakness of this study is that there were only 1-3 years of data from before construction and only 6 years of after-construction data. For irradiance data, there were no before data; we can only compare the difference between impact and control areas after the construction of the causeway.

RESULTS

Irradiance

Levels of underwater irradiance varied greatly among years and sites and were related to differences in water transparency and not variation in surface insolation (Dunton, 1990). Of the seven sites sampled, continuous year-round measurements were obtained for impact sites W-2 and E-2 and control site DS-11. A summary of the mean levels of irradiance at the two impact sites versus DS-11 showed that peak summer levels occurred in 1986 and 1990 and minimum levels occurred in 1988 and 1991 (Fig. 3). Except for 1990, impact and control areas had generally similar irradiance values during summer. In 1990, the "impact" irradiance level was reduced by a low value observed at W-2 (7.5 $\mu mol \cdot m^{-2} \cdot s^{-1}$). Table 1 shows that light levels at sites W-1 and W-2 during summer were consistently lower than any

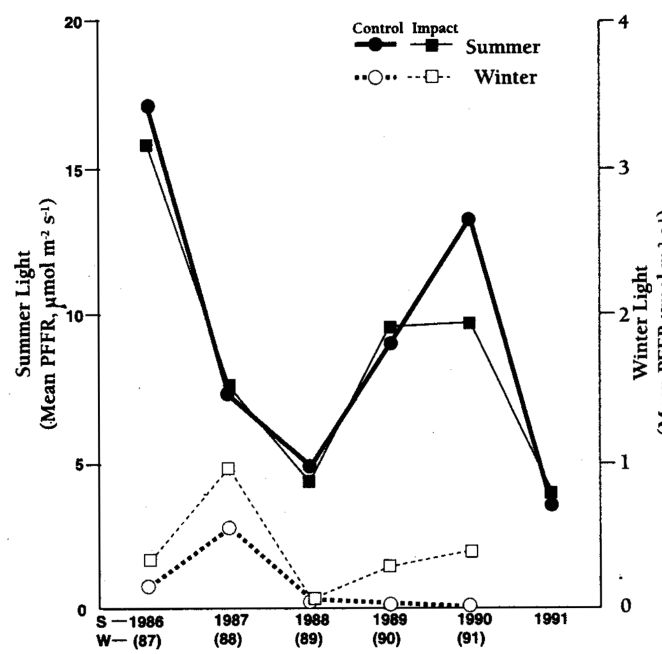

FIG. 3. Mean summer and winter light levels at impact (E-2, W-2) and control (DS-11) sampling sites, 1986-91.

TABLE 1. Mean photon flux fluence rates (PFFR, $\mu mol \cdot m^{-2} \cdot s^{-1}$) of all available summer irradiance data

Site	1986 (11 Aug-30 Sep)	1987 (7 Jul-30 Sep)	1988 (1 Jul-30 Sep)	1989 (15 Jul-30 Sep)	1990 (25 Jun-30 Sep)	1991 (11 Jul-19 Aug)
W-1	—	—	—	8.6	6.8	1.8
W-2	11.0	6.3	4.0	6.1	7.5	3.1
W-3	—	—	5.6	8.3	9.4	2.5
E-1	—	—	—	12.9	11.4	5.0
E-2	20.6	8.9	4.8	13.0	11.9	4.8
E-3	—	—	6.9	15.3	15.6	5.8
DS-11	17.1	7.3	4.9	9.0	13.3	3.6
Surface	200.4	211.8	221.2	227.0	278.4	349.3

— No data.

of the sites sampled, supporting the baseline observation that this area was naturally more depositional than the other sites. A possible explanation is that the small size of the sediments in this area (silty-clay) would be more easily suspended than the larger grain size of the sediments present in the other areas sampled.

In general, less than 10% of the annual solar input for Boulder Patch kelp is received during the 8-month period of ice cover (Dunton, 1990). However, if light is received during this period, it is highly utilized and can result in a 30-40% increase in annual growth, depending on carbohydrate reserves (Dunton, 1984, 1990). Mean levels of winter irradiance at the impact sites (W-2, E-2) exceeded that received at the control site (DS-11) in every year (Fig. 3). Peak levels of winter irradiance were received in both impact and control areas during 1987. DS-11, the control, was characterized by very low levels or no irradiance during the winters of 1988, 1989, and 1990. Based upon these observations, kelp growth at this site during these years was not expected to exceed 25 cm (Dunton *et al.*, 1982).

Kelp Health

Kelp health (as reflected by the related indices of tissue density and carbon content) and irradiance data exhibited similar annual trends (Fig. 4; see also Fig. 3). In 1988 and 1991, the plants stored very little carbohydrate. Low carbohydrate levels would be expected to be followed by years of reduced kelp growth, and in fact the lowest kelp growth was observed in 1989 (Dunton, 1990). Consequently, low kelp growth was expected for 1992.

Carbohydrate levels in 1986, 1987, and 1989 were about equal, in the mid-range of observed values, and a peak level of carbohydrate storage occurred in 1990 (Fig. 4). The mid-range values were associated with an irradiance peak in 1986 and mid-range irradiance levels in 1987 and 1989. In 1990, peaks occurred in both the irradiance and carbohydrate storage indices (Fig. 4). The apparent correlation between carbohydrate storage and irradiance is strongly leveraged by the 1988 low and the 1990 peak observed in both data sets.

The means of kelp health parameters were similar in the impact and control areas (Fig. 4). The observed differences in health parameters between impact and control sites in 1984 fell within the 95% confidence intervals of the post-construction means. However, difference between impact and control sites appeared to be less in the post-construction period than in 1984.

Kelp Growth

Annual patterns in linear growth of the first blade of *L. solidungula* for the period 1983-91 are shown in Figure 5. Annual trends in growth at both impact and control sites were similar, but growth at the control sites was consistently higher than at impact sites (Fig. 5). The mean of the observed post-construction differences was higher than the mean observed for the pre-construction years, but the two means had overlapping 95% confidence intervals. The difference in pre-construction means is strongly influenced by the 1984 data, when growth at the impact and control sites was almost identical. During 1983 and 1985, the difference levels were within the range observed in the post-construction period (Fig. 5).

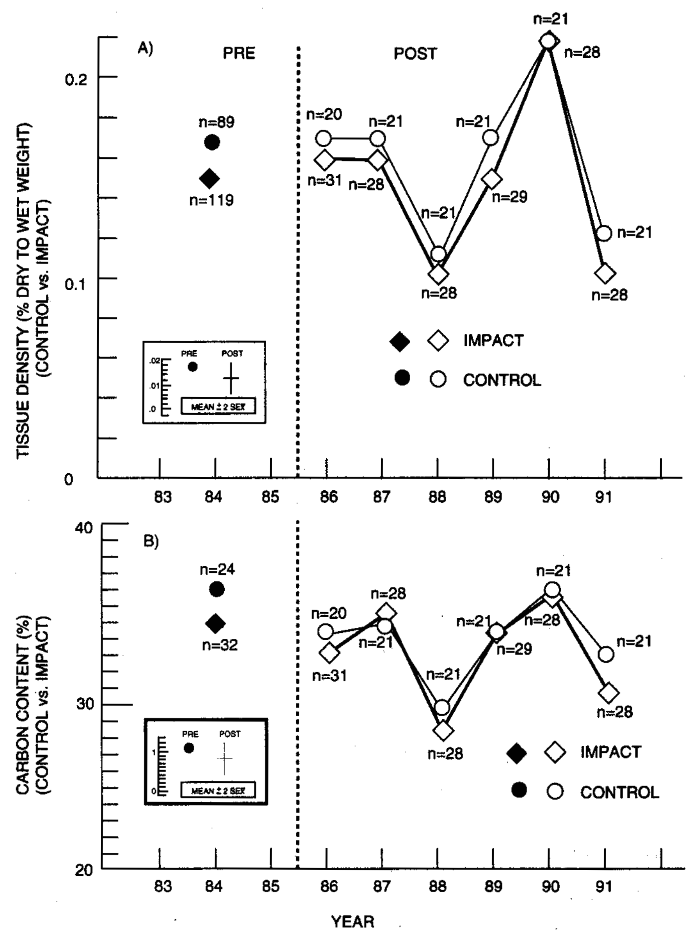

FIG. 4. Mean tissue density (A) and carbon content (B) of the kelp *Laminaria solidungula* at impact (E-1, E-2, W-1, and W-2) and control (DS-11, E-3, and W-3) sampling sites prior to (1984) and after (1986-91) construction of the Endicott Development Project. The inset at the left of each section shows the difference between impact and control sites observed in 1984 as compared to the mean difference (±2 standard errors of the mean) for the post-construction period 1986-91.

The lowest post-construction growth occurred in 1989, following the low light levels of the summer of 1988 (see Fig. 3). As a result of these low light levels, the kelp were unable to accumulate sufficient carbohydrate reserves to allow growth at higher rates (see Fig. 4). Based upon the low light and tissue density levels observed in the summer of 1991, kelp in the study area were expected to exhibit poor growth in summer 1992.

Community Structure and Diversity

We found that community structure was similar to that reported by Dunton and Schonberg (1981). A total of 26 attached, non-motile taxa was recorded from the individual quadrat photographs during the seven years of the study (Table 2). The number of observed taxa declined (as did the number of quadrats photographed) from 22 taxa (63 quadrats) in 1984 to 15 taxa (38 quadrats) in 1991. The most frequently occurring taxa in all years were three algae, *Phycodrys rubens*, *Coccotylus truncata*, and *Leptophytum* spp.; the

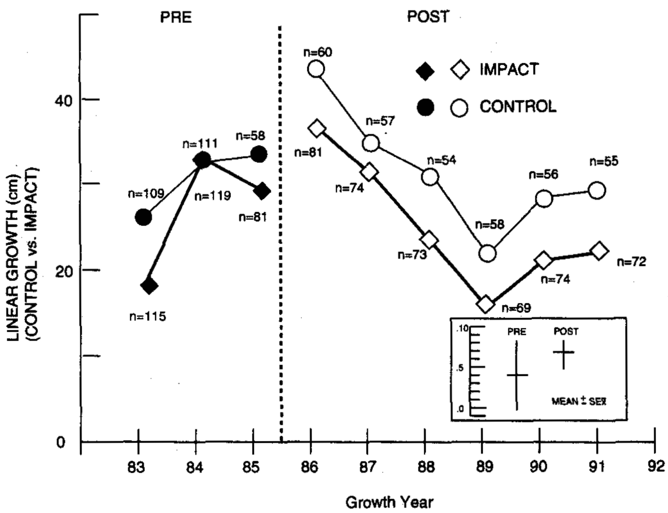

FIG. 5. Mean linear growth of the kelp *Laminaria solidungula* at impact (E-1, E-2, W-1, and W-2) and control (DS-11, E-3, and W-3) sampling sites prior to (1983-85) and after (1986-91) construction of the Endicott Development Project. Inset at lower right shows the mean difference (±2 standard errors) between impact and control sites for the pre- and post-construction periods.

sponge *Halichondria panicea*; and the hydroid *Sertularia cupressoides*.

Community structure remained relatively stable over the seven years of the study, at least in terms of the relative abundance of the dominant species (Table 2; Fig. 6). In Figure 6, the frequency of taxa seen in photographs in 1984 is compared to the frequency of taxa seen on the same rocks still present in 1991. The most important difference is the absence of five species in 1991 that, while present, were rare in 1984 (either 1 or 2 occurrences in the 38 photographs constituting the sample). This difference could be attributable to the higher frequency of *Phycodrys rubens* in 1991 as compared to 1984. *Phycodrys rubens* is a leafy algae, and in those years in which it was observed with higher frequency it also exhibited high growth levels. The leafy blades of the larger plants may have hidden rare species from view.

Site-by-year trends in taxa diversity (H″) differed between impact and control areas (Fig. 7). Taxa diversity at the control sites declined between 1984 and 1991, with all post-construction values lower than the control value observed in the 1984 pre-construction study. Taxa diversity at the impact sites was somewhat higher in 1986 and 1987 than in 1984, then dropped to slightly lower levels in 1988 and 1989, before declining sharply in 1990 and 1991. The overall trend for both impact and control areas was one of decline (Fig. 7). However, the difference in taxa diversity between the control and impact area in 1984 was greater than any differences observed in the 1986-91 post-construction monitoring program.

Colonization

Colonization of bare boulders placed at sites DS-11, E-1, and W-1 in August 1984 occurred slowly (Table 3). Colonization in 1986 and 1987 was described as negligible (Martin *et al.*, 1988), although there was early episodic colonization dominated by the polychaete *Spirorbis* sp. By

TABLE 2. Summary of photographic quadrat data for all sites in each year where the species counts are the number of quadrats in which the taxa were represented

	1984	1986	1987	1988	1989	1990	1991
Number of quadrats	63	55	52	40	47	38	38
Taxa							
Algae							
Pilayella littoralis	3	2	0	0	0	0	0
Laminaria saccharina	0	0	0	1	0	0	0
Laminaria solidungula	19	17	14	10	15	8	8
Ceratocolax hartzii	0	0	2	0	0	0	0
Chaetomorpha melagonium	0	0	1	0	0	0	0
Dilsea integra	5	4	3	3	2	1	2
Leptophytum spp.	20	23	24	22	24	16	15
Odonthalia dentata	15	18	19	8	8	8	5
Phycodrys rubens	49	49	49	33	42	33	35
Coccotylus truncata	39	41	28	20	32	24	17
Rhodomela spp.	17	22	20	6	7	6	3
Sponges							
Choanites lutkenii	2	1	1	1	0	0	0
Halichondria panicea	39	41	33	22	29	21	9
Haliclona rufescens	13	6	6	6	10	6	0
Phakettia cribrosa	9	10	15	12	12	11	5
Suberites sp.	1	0	0	0	0	0	0
Hydroid							
Sertularia cupressoides	37	26	25	27	24	19	10
Coral							
Gersemia rubiformis	14	12	7	8	6	4	1
Anemone							
Unidentified anemone	1	0	0	1	1	0	0
Bryozoans							
Alcyonidium gelatinosum	1	0	0	0	1	0	2
Eucratea loricata	8	8	7	3	5	1	1
Flustra carbasea	0	1	2	0	0	0	0
Flustra gigantea	3	3	0	0	0	0	0
Flustra sp.	1	2	3	3	1	1	1
Flustrella sp.	5	7	1	3	2	1	1
Ascidian							
Molgula griffithsii	2	4	3	1	0	0	0
Summary statistics							
Diversity	2.59	2.56	2.53	2.50	2.40	2.31	2.18
SD H″ (X2)	0.09	0.09	0.10	0.11	0.10	0.11	0.17
Evenness	0.84	0.85	0.84	0.85	0.85	0.85	0.81
Richness	3.68	3.34	3.41	3.43	2.96	2.76	2.95
Number of taxa	22	20	20	19	17	15	15

1989, photographs revealed that boulder DS-11 at the control site was inhabited by six species of epilithic organisms. In 1990, six years after deployment, this same boulder had five colonizing species, including a new arrival, the soft coral *Gersemia rubiformis* (Table 3). However, two taxa that were evident in the 1989 photograph of this boulder were not seen in the 1990 photograph, possibly due to heavy siltation of the rock. The mean number of species on individual quadrat

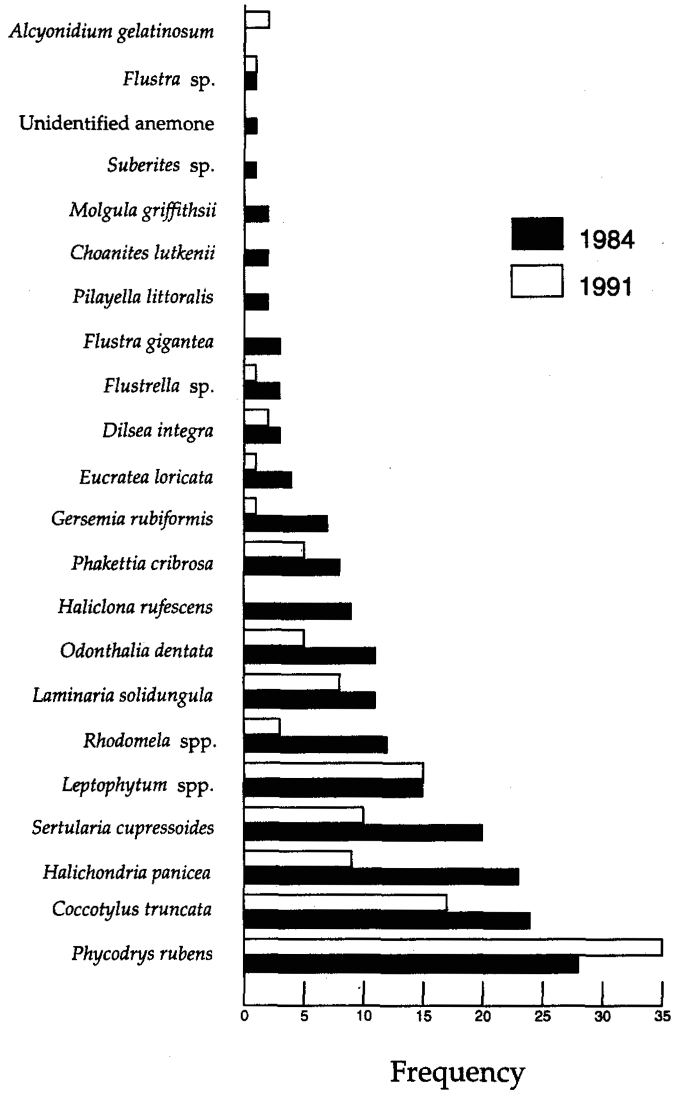

FIG. 6. Comparative community structure of the Boulder Patch between 1984 and 1991. Frequency comparisons are based on the 38 quadrats common to the first and last year of the study.

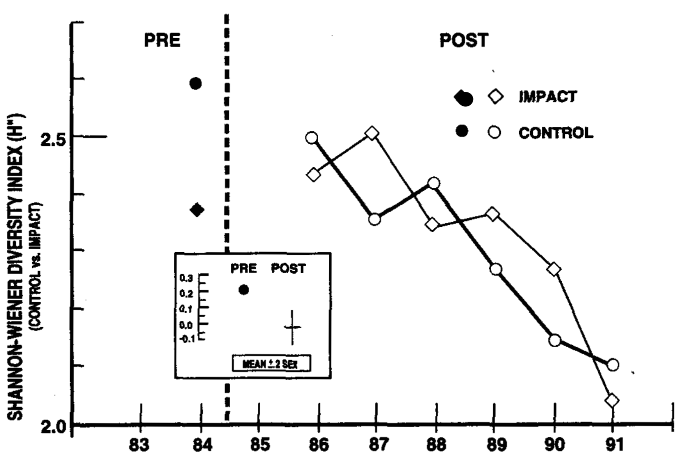

FIG. 7. Mean diversity levels (H") of Boulder Patch biota observed at impact (E-1, E-2, W-1, and W-2) and control (DS-11, E-3, and W-3) sampling sites prior to (1984) and after (1986-91) construction of the Endicott Development Project. The inset at the lower left shows the difference between impact and control sites observed in 1984 as compared to the mean difference (±2 standard errors) for the post-construction period 1988-91.

boulders photographed at site DS-11 in summer 1990 was also five. In 1991, the same six species apparent in 1989 were again seen in the photograph of boulder DS-11-R-1. The small *G. rubiformis* seen in 1990 was either not visible in the 1991 photograph or was absent. These data suggest that bare rock placed on the bottom in 1984 was fully colonized after five to six years.

Colonization of boulder W-1-R-1 at impact site W-1 showed an increase from three species in summer 1989 to six species in 1991. An additional three species (total of nine) were found when this boulder was examined in the laboratory (Table 3). Similarly, photographs of boulders E-1-R-1 and E-1-R-2 at impact site E-1 showed increases from three and four species in summer 1988 to seven and nine species in 1991 respectively. Examination in the laboratory revealed two additional species on each boulder (Table 3).

When deployed in 1984, the colonization boulders were bare and were not positioned near other boulders in order to reduce rapid colonization by vegetative growth from bordering colonies. The slow appearance of colonizing organisms and the presence of uncommon species suggests that Boulder Patch species disperse as relatively long-lived larvae; the larvae grow very slowly; and/or the larvae may have a non-motile dispersal stage or be otherwise limited in terms of dispersal capabilities.

Assessment of Effects

The results of the BACI analyses suggested that there were no adverse effects from the development on the Boulder Patch biological communities (Figs. 4, 5, and 7). Differences in kelp health parameters between impact and control sites were less after development than in the pre-construction period (Fig. 4). Community structure was similar in 1991 to that observed in 1984 (Fig. 6), and differences in species diversity between impact and control sites were smaller after construction than before (Fig. 7). There was an increase in the mean difference in kelp growth between control and impact sites, which would be suggestive of an adverse effect, but the 95% confidence intervals of the two means overlapped (Fig. 5).

As noted above, kelp growth data are available for site DS-11 for a total of 15 years, 9 pre-construction and 6 post-construction (Fig. 8). Comparison of these show there was little difference in kelp growth between the pre- and post-development periods at DS-11 (Fig. 8). The mean annual growth for the 9-year pre-development period was 28.3 cm, as compared to 28.0 cm for the 6-year post-development period. The variance was higher in the post-development period than in the pre-development period, with both the historical maximum (49.6 cm, 1986) and minimum (19.2 cm, 1991) growth observed after construction of the causeway. These post-development extreme values compare with pre-development extremes of 44.2 and 20.0 cm respectively.

DISCUSSION

Differences between impact and control sites of all the response variables were the same (or less) after construction and six years of operation of the development as they had

TABLE 3. Summary of species observed in photographs of colonization boulders at sites E-1, W-1, and DS-11 in years 1986-91; two colonization boulders were placed at each site in 1984; only boulders which were found in a particular year are included

	1986			1987			1988				1989		1990	1991			
Site	W-1-1	W-1-2	DS-11	E-1-2	W-1-2	DS-11	E-1-1	E-1-2	W-1-1	DS-11	W-1-1	DS-11*	DS-11	E-1-1	E-1-2	W-1-1	DS-11
Taxa																	
Algae																	
Laminaria solidungula															X		
Leptophytum spp.								X				X			X		X
Odonthalia dentata															X		
Phycodrys rubens			X*	X		X	X	X	X*	X	X	X	X	X	X	X	X
Coccotylus truncata		X															
Sponges																	
Halichondria panicea			X			X				X		X	X	X**		X**	X
Phakettia cribrosa														X**	X**	X**	
Hydroid																	
Obelia sp.														X			
Sertularia cupressoides											X	X	X		X	X	X
Tubularia sp.							X*	X									
Unidentified hydroid							X		X	X*							
Coral																	
Gersemia rubiformis													X			X**	
Polychaete																	
Spirorbis sp.	X	X		X	X		X	X	X	X	X	X	X	X		X	X
Crustacean																	
Unidentified barnacle														X	X		
Bryozoans																	
Alcyonidium gelatinosum														X	X	X	
Eucratea loricata														X	X	X	
Flustra sp.															X**		
Unidentified encrusting							X*	X*	X*	X*		X		X	X	X	X

*Identified *in situ*.
**Identified in the laboratory after collection.

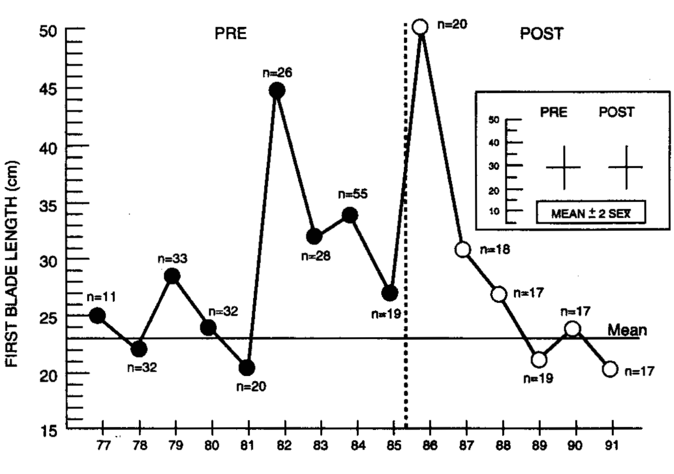

FIG. 8. Mean linear growth of the kelp *Laminaria solidungula* observed prior to (1977-85) and after (1986-91) construction of the Endicott Development Project. Inset at upper right shows the mean growth (±2 standard errors) for the pre- and post-construction periods.

been before the causeway was constructed. If adverse effects had occurred, an increase in the difference in response variables at control and impact sites would have been expected. We interpret the data to mean that there were no adverse effects from the development. An alternative explanation is that effects occurred but the controls might have been also affected by the project and were not truly "controls." A final thought is that the impact stations were not affected as had been predicted. We believe the latter is the case, as elaborated below.

Adverse effects from the development on the Boulder Patch were predicted to result from 1) the discharge of drilling fluids, which might reduce the levels of photosynthetically active radiation reaching kelp, increase sedimentation, and/or be toxic to the biota; 2) increased sedimentation and reduced light transmission from dredging a 788 m long and 91 m wide approach channel; and 3) changes in circulation resulting from the presence of the causeway, which might also increase sedimentation and reduce light transmission. Effects from the approach channel can be dismissed, because it was not required and was not dredged. The likelihood that adverse effects occurred at the impact sites from the discharge of drilling fluids and changes in circulation resulting from the presence of the development are discussed below.

Actual drilling-fluid discharges were far less than those hypothesized in the EIS as a result of down-annuli mud disposal procedures. Peak discharges of drilling muds were made on the ice during winter of 1986-87, and open-water discharges were restricted to 1986 and 1987 (Fig. 9). Maximum open-water discharges occurred during 1986, the year characterized by extremely high levels of underwater light in the Boulder Patch (see Fig. 3). Annual mud discharges from the Main Production Island (MPI) decreased from 24 000 bbls in 1986 (mostly made over ice) to 0 bbls in 1989. Similarly, mud discharges from the Satellite Drilling Island have been minimal since 1987.

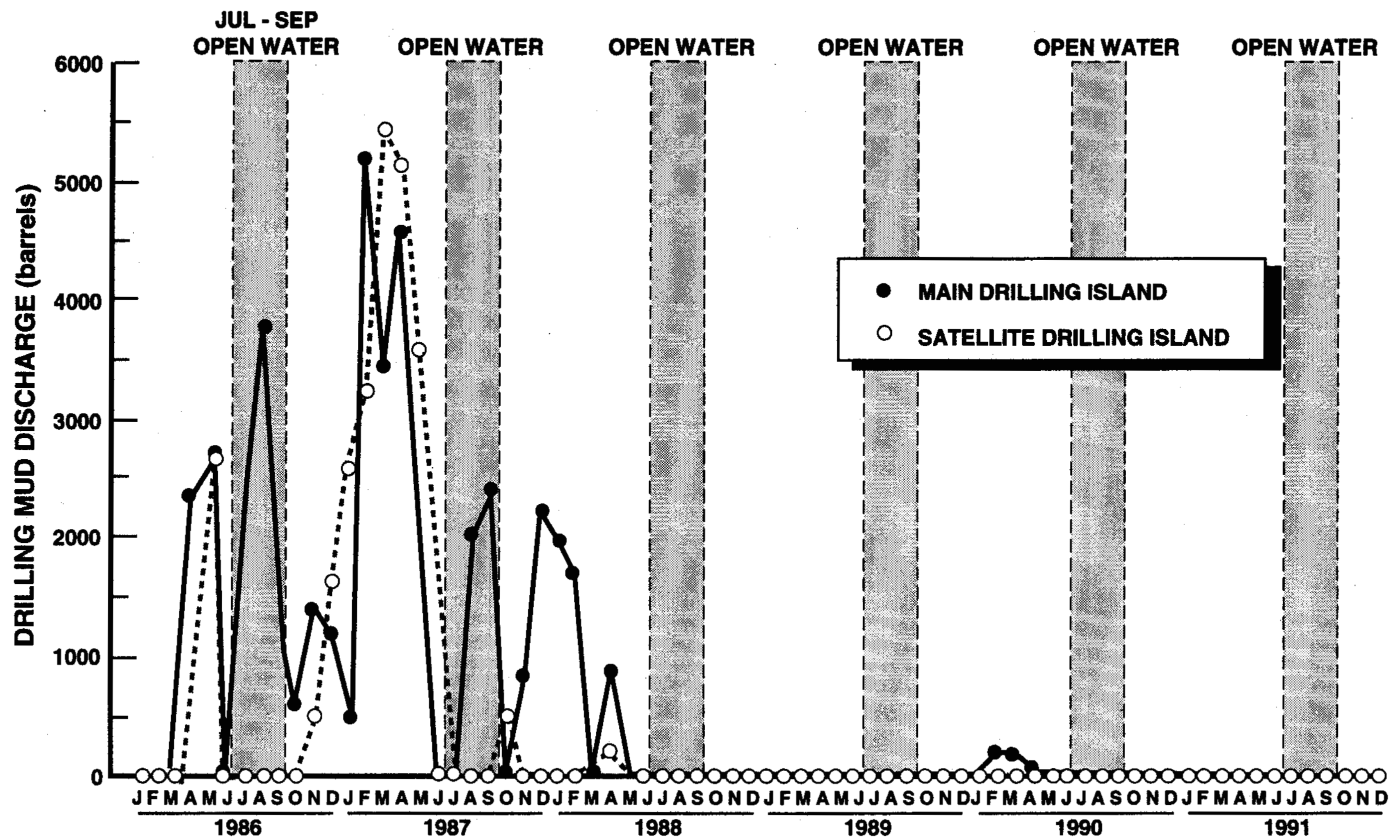

FIG. 9. Monthly discharges (barrels) of drilling muds from the Endicott Development Project, 1986-91. Shaded months represent the open-water period of each year. The location of the Main and Satellite Drilling islands is shown in Figure 2.

Results of comprehensive studies of the effects of drilling mud discharges on the environment and macroinvertebrate biota at and near the points of discharge were summarized by ENSR Consulting and Engineering (1991) for the period 1986-90. They found the area impacted by the presence of muds and cuttings (as evidenced by elevated barium concentrations) to extend only about 500 m to the northwest away from the MPI, approximately along the 3 m isobath. No effect on the composition of benthic macroinvertebrate communities was evident in the area of elevated barium concentration. These findings suggest that our impact sites in the Boulder Patch community would not have been affected by drilling mud discharges because of their distance from the highly localized impact areas.

Niedoroda and Colonell (1991) described sediment transport patterns in Stefansson Sound based upon sediment, oceanographic, and meteorological data from 1986. During west winds (~30% of the time), they found that sediment from the nearshore was moved eastward and offshore. Greatest deposition occurred on the upper shoreface, particularly at depths between 2 and 4 m (Niedoroda and Colonell, 1991). During east winds (winds are from the east ~60% of the time), sediment transport was to the west. However, the cross-isobath components of the sediment transport were difficult to distinguish for the east wind event (Niedoroda and Colonell, 1991).

Overall, the findings of Niedoroda and Colonell (1991) suggest that the event-scale patterns of erosion and deposition in Stefansson Sound are dominantly in the cross-shore direction out to depths of 2-4 m, generally short of the depths where rich biological communities occur in the Boulder Patch area. The overall pattern that is suggested is of large fluxes of sediment moving in broad, shallow zones. The shallow offshore profiles, fine sandy or silty bottom sediments, and high frequency of strong wind events suggest that in the Central Alaskan Beaufort Sea coastal ocean sediment deposits a few kilometres wide and many kilometres in longshore extent are created or destroyed by individual events. The annual and longer patterns result from averaging of these processes. There is a substantial westward net transport of sediments as a result of the greater frequency of east winds (Niedoroda and Colonell, 1991).

The Boulder Patch is generally deeper and east of the areas of greatest deposition shown by Niedoroda and Colonell (1991), and the net flux of sediments on an annual basis is westward, away from the Boulder Patch. These features probably account for the success of the community in its present location. The observed patterns also confirm that sediments of development origin would be transported westward away from the Boulder Patch.

DS-11 was observed to be shaded by a turbid surface-water plume frequently on east winds during late summer (Fig. 10). This plume, when present, was clearly detached or separate from any turbid waters emanating from the shoreline or from the development. On at least some occasions, we believe that this plume is from the Mackenzie River, located some 500 km east of the Sagavanirktok River delta. Whatever its origin, this turbid water apparently results in turbid ice over DS-11

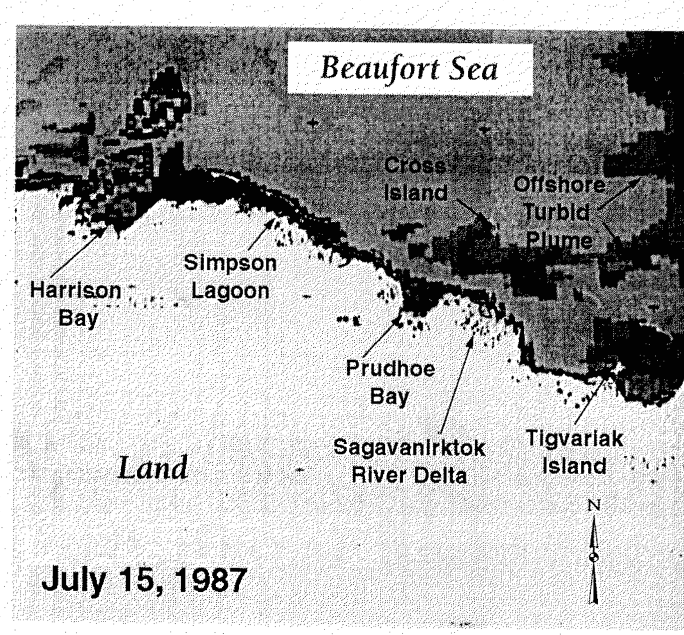

FIG. 10. Advanced Very High Resolution Radiometer (AVHRR) satellite imagery of the central Alaska Beaufort Sea taken 15 July 1987. The imagery, which has been enhanced and inverted, shows the incursion of a turbid plume of water from offshore into Stefansson Sound to the vicinity of our control sampling sites. Other imagery show the source of these waters to be the Mackenzie River, the mouth of which is some 500 km to the east.

during most years. During 1987-91 (post-Endicott) the presence of turbid ice at this site was suggested by the winter light measurements during 3 of the 5 years sampled, or 60% of the time. However, pre-Endicott kelp growth patterns for 1977-79 suggested turbid ice was present at DS-11 over 80% of the time (Dunton, 1984).

CONCLUSIONS

We conclude that the development has not adversely affected Boulder Patch habitat or biota, since none of the measured response variables showed significant increases in the differences between impact and control sites in the post-construction period when compared to the pre-construction period. The most likely reason that there has been no effect is that the Boulder Patch is located in deeper water, generally offshore and east of areas where sediments from nearshore are deposited on west winds; and, on east winds, sediments are moved shoreward and westward away from the Boulder Patch. Results of our colonization studies suggest that localized patches of Boulder Patch biological communities could be re-established if lost to a future development. Rock cover placed on the bottom following removal of the impact in these areas would ultimately be colonized. The time frame required for community development would be on the order of a decade.

Our conclusions are supported by the results of sediment quality and benthic macroinvertebrate monitoring studies independently conducted over the same time frame (ENSR Consulting and Engineering, 1991). These studies documented that adverse effects were few and restricted to areas within 500 m of the source.

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REFERENCES

DAHLBERG, M.P., and ODUM, E.P. 1970. Annual cycles of species occurrence, abundance, and diversity in Georgia estuarine populations. American Midland Naturalist 83(2):382-392.

DUNTON, K.H. 1984. An annual carbon budget for an arctic kelp community. In: Barnes, P., Schell, D., and Reimnitz, E., eds. The Alaska Beaufort Sea ecosystem and environment. Orlando: Academic Press. 311-326.

______. 1990. Growth and production in *Laminaria solidungula*: Relation to continuous underwater light levels in the Alaskan High Arctic. Marine Biology 106:297-304.

DUNTON, K.H., and JODWALIS, C.M. 1988. Photosynthetic performance of *Laminaria solidungula* measured *in situ* in the Alaskan High Arctic. Marine Biology 98:277-285.

DUNTON, K.H., and SCHELL, D.M. 1986. A seasonal carbon budget for the kelp *Laminaria solidungula* in the Alaskan High Arctic. Marine Ecology Progress Series 31:57-66.

DUNTON, K.H., and SCHONBERG, S.V. 1981. Ecology of the Stefansson Sound kelp community: II. Results of *in situ* and benthic studies. In: Broad, A.C., *et al.* Environmental assessment of selected habitats in the Beaufort and Chukchi littoral system. Annual Report, April 1981, in Environmental assessment of the Alaskan Continental Shelf. Available at NOAA Arctic Environmental Assessment Center, Grace Hall, Suite 300, 4230 University Drive, Anchorage, Alaska 99508. 65 p.

DUNTON, K.H., and SCHONBERG, S.V. 1990. Dark respiration, linear growth, tissue density and carbon content in *Laminaria solidungula*. In: Endicott Beaufort Sea Boulder Patch Monitoring Program (1988-89), Annual Report. Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. P. 3-1 to 3-24.

DUNTON, K.H., MARTIN, L.R., and GALLAWAY, B.J. 1985. Boulder Patch summer studies (1984) for the Endicott Development. In: Gallaway, B.J., and Johnson, S.R., eds. Environmental monitoring studies (Summer 1984) for the Endicott Development. Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 54-213.

DUNTON, K.H., REIMNITZ, E., and SCHONBERG, S. 1982. An arctic kelp community in the Alaskan Beaufort Sea. Arctic 35:465-484.

ENSR CONSULTING AND ENGINEERING. 1991. Endicott Development Project NPDES Monitoring Program Permit No. AK-003866-1. Sediment quality and benthic macroinvertebrate monitoring, 1990 studies. Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612.

GALLAWAY, B.J., and MARTIN, L.R., eds. 1987. Endicott Beaufort Sea Boulder Patch Monitoring Program (Summer 1986). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 113 p. + appendices.

GALLAWAY, B.J., MARTIN, L.R., and DUNTON, K.H. 1988. Endicott Beaufort Sea Boulder Patch Monitoring Program (1986-1987). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 127 p. + appendices.

LGL ECOLOGICAL RESEARCH ASSOCIATES, INC., and DUNTON, K.H. 1989. Endicott Beaufort Sea Boulder Patch Monitoring Program (1987-1988). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 98 p. + appendices.

LGL ECOLOGICAL RESEARCH ASSOCIATES, INC., and DUNTON, K.H. 1990. Endicott Beaufort Sea Boulder Patch Monitoring Program (1988-1989). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 107 p. + appendices.

LGL ECOLOGICAL RESEARCH ASSOCIATES, INC., and DUNTON, K.H. 1991. Endicott Beaufort Sea Boulder Patch Monitoring Program (1989-1990). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 123 p. + appendices.

LGL ECOLOGICAL RESEARCH ASSOCIATES, INC., and DUNTON, K.H. 1992. Endicott Beaufort Sea Boulder Patch Monitoring Program (1984-1991). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. 161 p. + appendices.

MARTIN, L.R., GALLAWAY, B.J., SCHONBERG, S.V., and DUNTON, K.H. 1988. Photographic studies of the Boulder Patch epilithic community. In: Gallaway, B.J., Martin, L.R., and Dunton, K.H., eds. Endicott Beaufort Sea Boulder Patch Monitoring Program (1986-1987). Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612. P. 5-1 to 5-13.

MILLER, D.L., and ENGLAND, J.M. 1982. Geotechnical engineering considerations, Duck Island Development Project, Beaufort Sea, Alaska. Exxon Company, U.S.A. Unpubl. ms. Available at Harding Lawson Associates, P.O. Box 578, Novato, California 94948. 35 p.

NIEDORODA, A.W., and COLONELL, J.M. 1991. Regional sediment transport in the coastal boundary layer of the central Alaskan Beaufort Sea. Coastal sediments '91. Proceedings of a Specialty Conference of the American Society of Civil Engineers held in Seattle, WA. 1488-1502.

PIELOU, E.C. 1966a. Shannon's formula as a measure of specific diversity: Its use and misuse. American Naturalist 100:463-465.

______ . 1966b. The measurement of diversity in different types of biological collections. Journal of Theoretical Biology 13:131-144.

REIMNITZ, E., and ROSS, C.R. 1979. Lag deposits of boulders in Stefansson Sound, Beaufort Sea, Alaska. U.S. Geological Survey Open File Report 179-1205. Available at U.S. Geological Survey, Menlo Park, California 94025. 26 p.

REIMNITZ, E., and TOIMIL, L. 1976. Diving notes from three Beaufort Sea sites. In: Barnes, P., and Reimnitz, E. Geologic processes and hazards of the Beaufort Sea shelf and coastal regions. Unpubl. ms. Available at NOAA Arctic Environmental Assessment Center, Grace Hall, Suite 300, 4230 University Drive, Anchorage, Alaska 99508. Attachment J. 7 p.

STEWART-OATEN, A., MURDOCH, W.M., and PARKER, K.P. 1986. Environmental impact assessment: "Pseudoreplication" in time? Ecology 67:929-940.

TOIMIL, L.J., and ENGLAND, J.M. 1980. Investigation of rock habitats and sub-seabed conditions, Beaufort Sea, Alaska. Unpubl. ms. Available at Harding Lawson Associates, P.O. Box 578, Novato, California 94948.

U.S. ARMY CORPS OF ENGINEERS (USACE). 1984. Final environmental impact statement: Endicott Development Project. Anchorage, Alaska. 3 vols. Unpubl. ms. Available at BP Exploration (Alaska) Inc., P.O. Box 196612, Anchorage, Alaska 99519-6612.