MARINE BIODIVERSITY MONITORING

PROTOCOL FOR MONITORING OF SEAWEEDS

A REPORT BY THE MARINE BIODIVERSITY MONITORING COMMITTEE (ATLANTIC MARITIME ECOLOGICAL SCIENCE COOPERATIVE, HUNTSMAN MARINE SCIENCE CENTRE) TO THE ECOLOGICAL MONITORING AND ASSESSMENT NETWORK OF ENVIRONMENT CANADA

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I. Rationale

Before explaining the justification of considering seaweeds in any coastal biodiversity monitoring program, it is essential to try to define this group of organisms commonly referred to as "seaweeds". Unfortunately, it is impossible to give a short definition because this heterogeneous group is only a fraction of an even less natural assemblage, the "algae". In fact, algae are not a closely related phylogenetic group but a diverse group of photosynthetic organisms (with a few exceptions) that is difficult to define, by either a lay person or a professional botanist, because they share only a few characteristics: their photosynthetic system is based on chlorophyll *a*, they do not form embryos, they do not have roots, stems, leaves, nor vascular tissues, and their reproductive structures consist of cells that are all potentially fertile and lack sterile cells covering or protecting them. During their evolution, algae have become a very diverse group of photosynthetic organisms, whose varied origins are reflected in the profound diversity of their size, cellular structure, levels of organization and morphology, type of life history, pigments for photosynthesis, reserve and structural polysaccharides, ecology and habitats they colonize. Blue-green algae (also known as Cyanobacteria) are prokaryotes closely related to bacteria, and are also considered to be the ancestors of the chloroplasts of some eukaryotic algae and plants (endosymbiotic theory of evolution). The heterokont algae are clearly related to oomycete fungi. At the other end of the spectrum (one cannot presently refer to a typical family tree), green algae (Chlorophyta) are closely related to vascular plants (Tracheophyta). Needless to say, the taxonomic classification of algae is still the source of constant changes and controversies, especially recently with new information provided by molecular techniques (van den Hoek *et al*. 1995). Moreover, the recent study by John (1994), suggesting that the roughly 36,000 known species of algae represent only about 17% of the existing species, is a measure of our still rudimentary knowledge of this group of organisms. According to Dring (1982), over 90% of the species of marine plants are algae, and roughly 50% of the global photosynthesis on this planet is algal derived (John 1994). Thus every second molecule of oxygen we inhale was produced by an alga, and every second molecule of carbon dioxide we exhale will be re-used by an alga (Melkonian 1995).

Despite this fundamental role played by algae, these organisms are routinely omitted from the biodiversity debate (Norton *et al.* 1996). For example, the recommendations from the United Nations Convention on Biological Diversity do not mention algae, and it is only recently that the International Plant Genetics Research Institute in Rome acknowledged that the world's crops do not all grow on land! For mostly emotional reasons and public appeal, tropical forests and other terrestrial ecosystems have been the focus of the biodiversity debate. The diversity of the marine and freshwater habitats has been overlooked, even though the number of phyla in the oceans is almost double that on land (Sepkoski 1995) and the abundance and significance of picoplankton has only been recently realized (Thomsen 1986). The highest estimate of the number of species in the sole class of the Bacillariophyceae (diatoms) may reach 10 million (John 1994), and is 20 times higher than that for all the higher plants and 35 times higher than that for beetles (Norton *et al.* 1996)!

In any typical Botany course that includes a survey of the plant kingdom, algae are generally often studied first, and rapidly, leaving a strong impression on students, at least partly due to the staggering variety of life histories. Apart from this, there are multiple reasons why algae should be fully considered in ecosystem biodiversity research and assessment: 1) the fossil record, while limited except in a few phyla with calcified or silicified cell walls, indicates that the most ancient organisms containing chlorophyll *a* were probably blue-green algae 3.5 billion years ago, followed later (900 million years ago) by several groups of eukaryotic algae, and hence the primacy of algae in the former plant kingdom (Round 1981); 2) the organization of algae is relatively simple, thus helping to understand the more complex groups of plants; 3) the incredible diversity of types of sexual reproduction, life histories, and photosynthetic pigment apparatuses developed by algae, which seem to have experimented "everything" during their evolution; 4) the ever-increasing use of algae as "systems" or "models" in biological or biotechnological research; 5) the unique position occupied by algae among the primary producers, as they are an important link in the food web and are essential to the economy of marine and freshwater environments as food organisms; 6) the driving role of algae in the earth's planetary system as they initiated an irreversible global change leading to the current oxygen rich atmosphere; by transfer of atmospheric carbon dioxide into organic biomass and sedimentary deposits, algae contribute to slowing down the accumulation of greenhouse gases leading to global warming; through their role in the production of atmospheric dimethyl sulfide (DMS), algae are believed to be connected with acidic precipitation and cloud formation which leads to global cooling; and their production of halocarbons could be related to global ozone depletion; 7) the incidence of algal blooms, some of which being toxic, seems to be on the increase in both freshwater and marine habitats (Hallegraeff 1993); and 8) the ever-increasing use of algae in pollution control, waste treatment, and biodiversity monitoring.

The present protocol restricts itself to seaweeds, which can be defined as marine benthic macroscopic algae members of the divisions Chlorophyta, Phaeophyta, and Rhodophyta. To a lot of people, seaweeds are rather unpleasant organisms: these plants are very slimy and slippery and can make swimming or walking along the shore an unpleasant experience to remember! To put it humorously, seaweeds do not have the popular appeal of what I call "emotional species": only a few have common names, they do not produce flowers, they do not sing like birds, and they are not as cute as furry mammals! However, the introduction to the well known amateur Collins Pocket Guide to the Sea Shore (Barrett and Yonge 1977) sums it up rather well: "seaweeds are certainly not easy to identify but in nuance of colour and rhythm of pattern they are beautiful plants and worth closer study than they usually receive". One of the key reasons for regularly ignoring seaweeds, even in coastal projects (what I refer to as the "zoologist bias" or the "kingdom neutral incorrectness"!), is in fact this very problem of identification, as very few people, even among botanists, can identify them correctly. Reasons for this include: a very high morphological plasticity; taxonomic criteria that are not always observable with the naked eye but are based on reproductive structures, cross sections, and increasingly ultrastructural and molecular arguments; an existing classification of seaweeds that is in a permanent state of revisions; and algal communities with very large numbers of species from different algal taxa that are not always well defined. According to Ryther (1963), production of benthic seaweeds has probably been underestimated, since it may approach 10% of that of all the plankton while only occupying 0.1% of the area used by plankton; this area is, however, crucial, as it is the coastal zone.

The academic, biological, and economic significance of seaweeds is not widely appreciated. The following is a series of arguments emphasizing the importance of seaweeds, and why they should be an unavoidable component of any coastal biodiversity and monitoring program:

• current investigations about the origin of the eukaryotic cell must include features of present day algae/seaweeds to understand the diversity and the phylogeny of the plant world, and even the animal world;

• seaweeds are important primary producers of oxygen and organic matter in coastal environments through their photosynthetic activities;

• seaweeds are food for herbivores, and indirectly carnivores, and hence part of the foundation of the food web;

• seaweeds participate naturally in nutrient recycling and waste treatment (these properties are also used "artificially" by humans, for example, in integrated aquaculture systems);

• seaweeds react to changes in water quality and can therefore be used as biomonitors of eutrophication. Seaweeds do not react as rapidly to environmental changes as phytoplankton but can be good indicators over a longer time span (days versus weeks/months/years) because of the perennial and benthic nature of a lot of them. If seaweeds are "finally" attracting some media coverage, it is, unfortunately, because of the increasing report of outbreaks of "green tides" (as well as "brown and red tides") and fouling species, which are considered a nuisance by tourists and responsible for financial losses by resort operators;

• seaweeds can be excellent indicators of natural and/or artificial changes in biodiversity (both in terms of abundance and composition) due to changes in abiotic, biotic, and anthropogenic factors, and hence are excellent monitors of environmental changes;

• around 500 species of marine algae (mostly seaweeds) have been used for centuries for food and medicinal purposes (Naylor 1977, Michanek 1979), directly (mostly in Asia) or indirectly, mainly by the phycocolloid industry (agars, carrageenans, and alginates). Seaweeds are the basis of a multibillion dollar enterprise (Radmer 1996) that is very diversified, including food, textile, pharmaceutical, cosmetic and biotechnological sectors. Nevertheless this industry is not very well known to Western consumers, despite the fact that we use seaweed products almost daily (Chopin *et al*. 1995). This is due partly to the complexity at the biological and chemical level of the raw material, the technical level of the extraction processes, and the commercial level of markets that are controlled by a limited number of companies worldwide (Chopin 1986);

• the vast majority of algal species has still not yet been screened for various applications, and their extensive diversity ensures that many new algal products and processes beneficial to mankind will be discovered.

Biodiversity monitoring studies are essential and should be carried out within a long-term frame of commitment, in terms of human resources and funding, to be fruitful and to avoid erroneous conclusions. It should be clear that the purpose of such studies is not only to publish a checklist at a certain time "t", but to measure how this checklist changes over time and space, and to partition this variance between what is due to natural variability and what is due to the impact of abiotic and biotic factors that are most often manipulated by humans. One of the ultimate goals of biodiversity studies could then be to develop models capable of predicting changes in biodiversity within the food web and the resultant impacts on the different organisms.

However, biodiversity studies are not without their shortfalls and limits. The biodiversity debate has focused on the species level even though no satisfying universal definition of a species has been established. Some authors have argued that changes in biodiversity would be much more detectable using higher taxonomic ranks (Raup and Sepkoski 1982). Myers (1986) indicated that increased biodiversity is a sign of healthy and stable ecosystems; however, the relative biodiversity of each area should be understood before reaching conclusions and comparing numbers. For example, in Brittany (France), which is a transition zone between the eastern province of the cold temperate atlantic-boreal region and the lusitanian province of the warm temperate mediterranean-atlantic region (van den Hoek 1975), 625 species of seaweeds have been identified (Feldmann and Magne 1964; the list has increased since). In comparison, in eastern Canada (from Labrador to the New Brunswick/Maine border), part of the western province of the cold temperate atlantic-boreal region, only 354 species of seaweeds are known (South 1984). The species richness of the two areas is obviously different; yet this does not mean that one area is healthier than the other. Another point to realize is that quite often biodiversity studies are initiated in a specific location after a natural, or human-created, catastrophic event (*e.g.* oil spill) has occurred. Consequently, one is generally missing the description and quantification of the "pristine" conditions at a "reference" site for establishing valid comparisons (in addition to the controversies surrounding the definitions of "pristine" and "reference"!).

Paramount to the integration of biodiversity studies, for obtaining meaningful long-term data series and comparisons over time and space, is the necessary standardization and maintenance of similar precision levels in the sampling, sample processing, and data analysis methodologies. The following section addresses this point, drawing attention to the particulars of seaweed biomonitoring, and realizing that standardization, while highly desirable, is not always attainable for many practical reasons.

II. Sampling

A proper assessment of biodiversity and monitoring requires sound standardized sampling procedures and correct identifications, which requires good taxonomic training and quality preserved specimens. The relevant ecological field methods relating to macroalgae are very well described in Littler and Littler (1985).

1. Field collecting for qualitative assessment (species richness)

If the prime objective of the study is to establish a comprehensive list of the species present in a region, very little simple equipment is needed: proper clothes for the region and season for collecting at low tide, or snorkling and SCUBA equipment for deeper subtidal near-shore sampling; knife, plastic and whirl-pak bags or buckets, fine-mesh (diving) bags, plastic vials, waterproof paper, pencil, etc. We exclude from this chapter the sampling of deep-water algae, necessitating the use of a submersible (Littler *et al*. 1986).

Attached seaweeds are preferred to beach-drift or storm-cast ones whose original habitat is unknown and that are generally damaged or decaying, causing problems in identification. An effort should be made to collect entire plants (including holdfast or rhizoidal portion) and reproducing specimens, as reproductive structures may be critical for identification.

Bottom trawls and grabs are generally not favoured methods by phycologists because of gear operating costs and sampling bias, the damage to specimens, and the fact that seaweeds are generally growing on relatively shallow and rocky substrata. For deep-water collections, a submersible is used.

It is desirable to collect during monthly or at least quarterly intervals at sites available year long, to detect not only perennial but also ephemeral species, and to document seasonality of morphological plasticity and phases of life-history (isomorphic or heteromorphic gametophytic and sporophytic generations). Some life-history phases of certain species, such as *Palmaria palmata*, *Laminaria* sp., are not discernible with the naked eye and lead to the conclusion that a particular species is not present, when it is only not visible. Developmental stages of other species can be morphologically completely different (*e.g.* erect frond of the gametophytic generation of *Mastocarpus* or crustose development of the sporophytic generation of *Petrocelis*). For these reasons, particular attention should be given to the date(s) of collection when comparing studies and lists of species. Another potential difficulty when comparing studies that must be taken into consideration is the differential size cut-off point for recording taxa between authors (basically naked eye versus dissecting microscope level).

Epiphytic species have often been neglected in the past (Mukai 1990). However, they should be an integral part of the sampling effort, as it is increasingly realized that they can play a key role in controlling some ecosystems [*e.g.* seagrass meadows (Hanisak

1995)].

2. Field collecting for quantitative assessment (species diversity)

Quantitative assessment is not only helpful for measuring biodiversity and its changes but also to evaluate standing stocks (quantity of seaweeds present at a particular time), standing crop (sustained harvestable biomass) for economically valuable species, resource allocations, biochemical constituents, population dynamics, and phyto- and zoo-associations.

To obtain these data, one has to make a fundamental choice in sampling strategy by choosing between a destructive or nondestructive sampling program. If possible, *i.e.* if knowledge can be gained equally well, nondestructive techniques should be preferred, or destructive methods should be minimized to avoid site destruction.

2.1 Destructive sampling

First, the site for sampling should be easily accessible under most weather conditions, easy to locate, and should tolerate repeated sampling. Materials such as anchor bolts, pitons, cement blocks, epoxy putty, flagging tapes, lines and buoys, spray paints, quadrats, and triangulations with shore landmarks, etc., have been used to clearly identify sites and transect lines (de Wreede 1985). The physical and biological conditions of the site will dictate the proper equipment to choose. Chopin and Kerin (unpubl.) are presently using anchor bolts, lines with small red buoys, and fluorescent flagging tapes to identify their quadrats in the intertidal/subtidal zones along the Bay of Fundy, Canada.

Most seaweeds can generally be removed with simple equipment, such as knife, paint scraper or clipper. Encrusting algae will require more effort, necessitating parts of the substratum to be collected with hammer or chisel. Samples can be collected in diving bags or plastic bags. A suction device (Levine 1984) can be useful, especially when collecting small species in the subtidal zone. For short trips, seaweeds should be kept moist with a minimal amount of seawater, until they are processed back in the laboratory. Using excess quantities of seawater, which heats up during transport, may lead to degradation of some species. Wrapping the seaweeds in damp paper towel or cheese cloth placed into plastic bags, and put in a cooler containing ice-packs or ice, is recommended for longer trips. During collection, required information on location, bag number, date, time, air and water temperature, salinity, etc. can be recorded on waterproof paper or plastic slates with a soft-lead pencil.

The scope of the sampling program is obviously limited by such factors as the number of people involved in the study, the duration and geographical boundaries of the program, and the availability of equipment and funding. Initial decisions will have to be made, such as developing an optimal balance between the number of stations, the frequency of sampling, and the number of samples of the appropriate unit size and shape at each station. Every sampling program should ideally start with a pilot study to assess the potential of sampling sites, preferably at different seasons, in relation to the question(s) asked.

Samples can be collected in either a random or regular fashion in extremely uniform locations. However, random sampling, in which the location of the sampling units along transect lines is determined using a random number table, is not always possible and/or desirable. This is because in many areas, such as the intertidal zone, there is a marked patchy distribution of certain species. Thus random sampling would lead to erroneous conclusions. Instead, a stratified random sampling strategy is recommended under these circumstances, where random sampling is conducted within patches of similar nature (Bellamy *et al.* 1973). Samples must be representative of a population as a whole, including its heterogeneity.

The purpose here is not to develop biostatistic/biometric arguments in favour of one type of experimental design. The reader is, instead, reminded of the constant debate regarding the definition of "the" basic stratified random sampling unit, the risk of pseudoreplication, the problems of nonreplaceable sites, the impacts of previous samplings and their effects on statistical analyses. This is particularly important for perennial plants and species with low recruitment capacity and/or at a disadvantage in plant/plant or plant/animal interactions. One could avoid such impacts by sampling over a very large area, but one then risks being criticized for collecting samples which are exposed to different environmental conditions and are, hence, not comparable. There is obviously no ideal approach and often what is considered to be the basic sampling unit depends on the conditions at the study site(s) and the hypotheses being tested. Moreover, one should not forget that the wonderful, ideal, theoretical world dreamt of by statisticians in front of a computer is in contrast to the real, "down to sea" situation marine biologists have to deal with!

Critical assessments of techniques for quantitative sampling of macrophytes are rare. Gonor and Kemp (1978), Pringle (1984), and de Wreede (1985) wrote concise papers on destructive sampling techniques and their efficiency. Issues such as sampling unit size (minimal area/species-area curves) and shape, sample number, sample frequency, sample efficiency, sample precision, and sample analysis according to the aim(s) of the study have to be addressed and determined before the start of a sampling program. The danger in sampling a new site or area is to blindly implement a sampling strategy described in a publication, without first investigating if that particular sampling strategy can be applied, or if it needs to be modified. As Schwenke (1972) correctly concluded, a single generally accepted technology for sampling benthic macrophytes simply does not exist.

Pringle (1984) reviewed 21 papers dealing with the determination of density, biomass, or species associations in the midlittoral or shallow sublittoral zones. The three most commonly used sampling unit shapes were the quadrat (66.7%), circle (19.0%), and rectangle (14.3%). A large proportion (42.9%) of these studies used sample unit areas below 0.25 m^2, 23.8% used 0.25 m^2, 28.6% used 1m^2, and 4.8% used areas larger than 1 m^2. The reasons for the choice of the unit areas were often not given. Pringle (1984) designed an experiment to determine which sample unit quadrat area would yield the greatest precision for the available resources (people and funding for time, boat, and SCUBA) when investigating commercial beds of the carrageenophyte *Chondrus crispus* (Irish moss) off western Prince Edward Island, Canada. If the only concern was time, a quadrat of 2.25 m^2 (1.5 m x 1.5 m) would have been recommended, as it took 182.5 min to evaluate a standardized biomass from a 20 m^2 area; in comparison, it took 364.0 min with a quadrat of 1 m^2 (1 m x 1 m) and 696.0 min with a quadrat of 0.25 m^2 (0.5 m x 0.5 m). However, the number of sample units and the sampling precision should also be considered. In that case, with an acceptable error of 10% (Southwood 1968), a quadrat of 0.25 m^2 was the most efficient and one of 1.56 m^2 (1.25 m x 1.25 m) the most inefficient (requiring 120.5% more time). A large number of small sample units (0.25 m^2) was more efficient than a small number of large sample units (4.0 m^2). This also increased the number of replicates and degrees of freedom. Based on these results, Pringle (1984) recommended the use of a 0.25 m^2 sampling unit, recognizing that it was best for the size and distribution of the macrophytes sampled at his particular site. Interestingly, de Wreede (1985) also determined that a sampling unit size of 0.25 m^2 was the most appropriate for his study of the standing stock of *Sargassum muticum* in the Strait of Georgia, British Columbia, Canada.

It is obvious that the size of the targeted organisms also is influential: Holme (1971) recommended a 1.0 m^2 area when sampling large benthic animals on a rocky shore and a 0.25 m^2 area for smaller animals. If larger kelps are present at a site, it is obvious that larger quadrats should be selected. The Environmental Monitoring and Assessment Network of Environment Canada would like to favour a standard quadrat area of 1 m^2. The effort of standardization is laudable, only if it would be for the sake of easier comparison between sites and studies through time; however, while an area of 1 m^2 may certainly be adequate for many studies, it may not always be the most appropriate sampling unit.

The optimal sampling unit size, which maximizes the number of different species in the sample, can be estimated as the point where a performance curve (number of species against cumulative sampling unit size) levels off (Pielou 1977). Gonor and Kemp (1978) recommended using the sampling unit size that minimizes the estimate of the variance of the mean.

The number of sampling units to be taken is not always easily determined either. It is recommended to take equal numbers of samples at the different study sites and at different times of the year, in order to facilitate subsequent statistical analyses. According to Brower and Zar (1977), the number of replicates is sufficiently large when the cumulative mean becomes insensitive to the variations in the data. In the ideal situation of random sampling, with the number of samples at each site and time equal to that required for the most diverse site/time, an index of precision D (in % of the mean) can be defined (Elliott 1977), from which the number of samples can be calculated:

$$D = 1 / \bar{x}\sqrt{s^2 / n}$$

where $\bar{x}$

is the mean, s the standard deviation, and n the number of sampling units. Very often this ideal situation is not met, and the above equation should be used as a guide to obtain the minimum number of sampling units required. The frequency of sampling will depend on the emphasis put on seasonal variations within a study, and previous knowledge of the magnitude of such variations. Chopin and coworkers, in their various studies on *Chondrus crispus* and *Ascophyllum nodosum* populations, have regularly used a sampling frequency of once per month to once every seven weeks (Chopin and Floc'h 1987, Chopin *et al.* 1987, Chopin *et al.* 1988, Chopin *et al.* 1990a, Chopin and Floc'h 1992, Chopin *et al.* 1992, Chopin *et al.* 1996a).

2.2 Nondestructive sampling

It should be clear that completely nondestructive studies are extremely rare (and would even be considered suspicious!) because normally some destructive sampling, also called "ground truthing", is required to calibrate and establish correlations with nondestructive measurements.

Nondestructive assessment techniques are very well suited for the monitoring of changes in biodiversity due to natural or anthropogenic factors, because these methods allow for the successive use of the same site without experimental manipulation and comparison to an initial time "t_0" (even if the latter has been arbitrarily fixed and does not necessarily reflect a community having reached a pristine state at equilibrium). Repeated locating of the same plants would be desirable and for this proper tagging devices should be used that are appropriate for the morphology and texture of the particular plants and their habitats. This will minimize mortality due to mechanical injury, abrasion, or increased drag force. Sharp and Tremblay (1985) developed a small monofilament tag, using surgical rubber and numbered plastic tubing, which was used successfully (less than 10% loss over 24 months) with fronds of *Chondrus crispus*. This tag, with some modifications, has also proven to be extremely reliable with *Ascophyllum nodosum* (Ang *et al.* 1993, Chopin and Kerin unpubl.). Some species, however, cannot be easily tagged because of their morphology or the damage tags would incur; consequently, these species have to be mapped with precise coordinate positions obtained from gridded quadrats or photographs.

The photogrammetric technique, with normal and infrared slide films, has been widely used to obtain, for example, quantitative information on species cover, density, and frequency (Littler and Littler 1985). This involves the simultaneous observation of two photographs of the same field, taken at a slightly different angle, to give a perceived three-dimensional image through a stereoscope. Quadrats are photographed perpendicular to the substratum. In the case of stratified seaweed communities, canopy-forming species can be photographed first, then moved aside for the time needed to photograph the lower layers. In the laboratory, the infrared and colour slides are projected simultaneously (the infrared below the colour) onto two sheets of fine-grained white Bristol paper with a grid pattern of dots at a density of 1 per cm^2. Replicate scorings are performed and percent cover values are expressed as the number of "hits" for each species divided by the total number of dots contained within the quadrat. For calculating cover area, a planimeter or an image analyzer can be used. Infrared films help to discern some groups of algae, like the Cyanobacteria, more reliably and can give a rapid assessment of the health of the plants (dead ramifications, with degraded chlorophyll, can be clearly observed). This technique is very appropriate for the study of the macroflora but macrophotogrammetry can also be used to work at a smaller scale. The photogrammetric technique avoids two problems associated with *in situ* observations: parallax error (due to movement of the observer and/or organisms relative to the sampling device) and variability of estimation among observers (scorings can be reviewed).

By coupling photogrammetric measurements with destructive assessments of biomass, it is possible to generate precise regressions and correlations, and subsequently interpolate biomass estimates from cover data for the most represented or abundant taxa. The comparison of photosamples of identical quadrats over time has also allowed photogrammetric techniques to be used for measuring diversity, and its changes due to stress, by the development of indices, often derived from terrestrial ecology. The problem with some indices is that richness and evenness can be confounded because of the underlying assumption that the ecological importance of a given species is proportional to its abundance. Morever, some species, although adding to the overall diversity, may not be ecologically significant players in their habitat, or may be replaceable by other existing species without apparent disturbance. In addition, some indices are not suited to coastal situations in which there are naturally few species (hence low diversity) or in which some species may be extraordinarily successful (hence low heterogeneity). A particular index should be evaluated at a pilot scale before being implemented, and, if possible, be used in conjunction with other indices derived from the same data sets to check its biological validity and its sensitivity to changes. A comparison between studies is sometimes also rendered difficult because of inadvertently amalgamating analyses of point diversity (-diversity), space diversity (ßdiversity), and time diversity (-diversity; if such nomenclature is accepted, following the Greek alphabet order).

Plotless methods, which reduce quadrat measurements to linear or point recordings of distances, have also been used for analysis, but are not as powerful for dense macrophyte communities, where it is often impossible to distinguish individual plants (Littler and Littler 1985). These techniques avoid the debates surrounding the selection of plot size and shape, and have been found more cost efficient than quadrat techniques by some authors. However, continuous line-intercept (transect) sampling is not as powerful in detecting subtle changes, and generally necessitates a very high number of points, not always selected without bias, before a representative sampling is carried out appropriately. Moreover, the use of plotless methods assumes that individuals from all species are randomly distributed, which is rarely the case along any shoreline.

Remote sensing by airplane (analog method) or satellite (numerical method) is also widely used and needed progress in increasing resolution has been achieved in recent years (Belsher *et al*. 1985). Automatic digital image processing of satellite data over several wavelengths provide thematic maps of seaweed distributions indicating surface cover, species or species-association density, temporal patterns, and health of stocks. Remote sensing interpretation still requires a significant amount of ground truthing but the advantage of this method is the possibility of rapidly and repeatedly surveying large regions, or areas inaccessible by land and sea. Remote sensing provides both qualitative (colour/false-colour infrared/spectral/radiometric signatures of species or associations) and quantitative (optical densitometry related to biomass) information. The most accurate results are obtained in the intertidal zone; interpretations regarding the subtidal zone are more complex due to the problems associated with the penetration of the signals/sensors through the water column.

III. Sample processing

Samples should be processed as soon as possible after collecting to avoid rapid fading and decaying. If necessary, specimens in plastic bags can be stored in a refrigerator overnight, or in a freezer for longer storage.

There are four basic methods of processing seaweeds to keep voucher specimens or to preserve for further identification:

• samples (especially large ones) can be mounted on herbarium paper, as much as possible with seawater, or by very rapid immersion in freshwater (prolonged exposure to freshwater destroys pigments). In case of epiphytic species, the host should be recorded and/or also mounted;

• small (a few cm) and delicate samples can be kept in individual vials filled with various preservatives (Tsuda and Abbott 1985). Common ones are 3-10% formalin in seawater with borax buffer, and 35-70% ethyl alcohol;

• very small specimens or parts of larger specimens can be mounted as microscope glass slides with, for example, the corn syrup/phenol or thymol method (Tsuda and Abbott 1985);

• a simple method of preservation and shipment is to cover samples with silica gel or any other desiccant and enclosing them in plastic bags or jars.

All processed samples should be kept away from light and humidity.

A sample is not completely processed until it is properly labeled and indexed. Labels should contain the binomial [including authority(ies)], date of collection, location (broad or narrow geographical range, coordinates), specific ecological niche (height on shore, depth, type of substratum, and other abiotic or biotic factors if needed or desired), name of collector, name of identifier, and name of herbarium where specimen was deposited.

Identifying some specimens to the species level can be a challenging, frustrating and humbling experience because the identification is often not only based on simple morphological criteria, but also on reproductive structures and types of life history, cross-sectional anatomical details, types of growth, cytological and ultrastructural criteria, and increasingly molecular evidence. For identification purposes there are several regional floras, illustrated keys, and checklists available that will suit identifiers ranging in competence from beginner to the "advanced" amateur taxonomist. This includes the following documents for the identification of common marine macrophytes along the East Coast of Canada: Taylor (1957), South and Cardinal (1973), Taylor (1981), South (1981; 1984), South and Tittley (1986), Bird and McLachlan (1992), and Villalard-Bohnsack (1995).

One principle not to forget in the process of identifying specimens is to go only to the lowest taxonomic level (preferably species level) at which one feels comfortable with the identification. If in doubt, one should not hesitate to contact the expert(s) to arrange shipment of samples for identification. This avoids costly misidentifications which could compromise the development of a study and its use for comparison to others.

In the beginning of a study it is also very important to choose between developing an exhaustive list of species (floristic approach), which requires precise and often very laborious identification investigations, or to restrict monitoring to key-species for which parameters like biomass, size, percent coverage, recruitment would be measured to record trends and changes over time.

The grouping of unidentified species in broad and vague categories (such as turf, crustose, filamentous, etc.) should be avoided, as these subjective groupings obviously vary according to authors, rendering comparison of studies very difficult. Moreover, taxonomic groupings generally do not reflect the different roles of the combined species in a community.

IV. General considerations on abiotic and biotic factors, and site selection

Morphological, biological, physiological, and ecological adaptations to abiotic and biotic factors, and their combination, has resulted in the geographical and vertical distribution and zonation of seaweeds on the shore. This distribution is not haphazard, as it is quite constant in similar habitats. There are, however, no sharp floristic boundaries but rather gradual transitions. For comparative biodiversity studies, it is, therefore, very important to choose sampling sites very carefully so that the comparison remains meaningful.

The zonation is particularly obvious on rocky shores, where even a superficial glance reveals the presence of successive belts of different colours, with limited vertical extent, representing different seaweeds and invertebrates. At first sight rocky shores could be considered as one of the most inhospitable environments, yet, especially in temperate zones, there is a profusion of algal growth, with each belt representing a distinct environment.

Seaweeds have been very successful at colonizing extremely diversified habitats in complex environments, where they have to constantly respond to a wide variety of ever-changing abiotic and biotic conditions. The most frequently cited abiotic factors controlling the distribution of seaweeds are: tidal rhythm (emersion/immersion and desiccating effect), degree of wave action, water flow, currents, light (both qualitative and quantitative aspects), temperature, type and orientation of substratum (and presence or absence of tide pools, crevices, overhangs, and caves), pressure, turbidity, salinity, pH, and concentration of nutrients, dissolved gases, and organic matter.

Biotic factors often cited are: grazing pressure, fungal and microbial activity, competition for substratum, protective cover against desiccation during emersion for intertidal algae, shading due to overgrowth, availability of host plants or animals (for obligate epiphytes, endophytes, epizootes, endozootes, and parasitic algae), and proximity to pollution and anthropogenic activities (agriculture, industries, aquaculture, etc.). Three types of biotic interactions are constantly at play on the shore: intra/inter-specific competition, herbivory, and, indirectly, carnivory. The importance of biotic factors in controlling coastal communities is often realized only after an ecological disturbance has been introduced naturally or intentionally by humans.

Changes in abiotic and biotic factors at different times of the year, or level of community maturity, will have different consequences because species will be impacted differently at different physiological stages, as will communities at distinct stages of succession. Hence, much work is still needed to refine standardized techniques of analysis and in describing discrete communities of defined spatial niches, which is essential to biodiversity monitoring.

V. Demographic studies

Biodiversity monitoring can also encompass demographic/population studies of a single species or of associations/communities of a few of them. The four primary parameters affecting the density and size of a population are natality, mortality, immigration, and emigration (the last two being of minor significance for benthic species with limited dispersal of reproductive organs). Secondary population parameters frequently studied include age class distribution, sex ratios, ploidy ratios, pool size and fertility of reproductive organs, age at first reproduction, reproductive life span, proportion of individuals reproducing at a given time, fecundity and fecundity/age regression, and reproductive effort versus growth and predator defense. These different parameters have been discussed by Chapman (1985, 1986). Intra- and interspecific interactions, and exploitative and interference competitions should also be considered (Denley and Dayton 1985), and not only at the plant/plant level but also at the plant/animal one. For example, moderate grazing pressure may increase the diversity of algal species by preventing dominance of large, canopy-forming species (Lobban and Harrison 1994).

Changes detected in demographic studies can be used in biodiversity monitoring as warning (or sometimes emergency!) signals, or to demonstrate that a disturbance has taken place. However, too often studies are initiated after a natural or human-created disaster took place, and no previous in-depth baseline description (t_0 of the affected ecosystem is available for comparison. Also subject to debate are studies comparing an impacted site to a so-called "reference/control" site: are the two sites really comparable, and what is a "pristine" site?

VI. Succession studies

The concepts of a steady-state equilibrium and climax community are more and more questioned as this state is rarely achieved in nature, especially with respect to algal vegetation (Foster and Sousa 1985). Successional processes are probably an integral part of most communities which are now more appropriately described as being in various, but permanent, states of recovery from natural or induced (most often by humans) disturbances. Species stability appears illusive in the phycological world, and succession processes seem to take place more often according to inhibition than facilitation or tolerance mechanisms (Chapman 1979; see appendix for more details). The intermediate disturbance theory (Connell 1978), which predicts that a habitat under "moderate" intensity of disturbance shows higher species diversity than stable or extremely unstable habitats, is also applicable to many macroalgal communities which can in fact, be considered as "dynamically stable". Successional stages should be taken into account in long-term biodiversity monitoring programs, as they induce natural changes which can be superimposed to other changes caused by other factors.

Unfortunately, few long-term studies to investigate the continuity of marine floras have been undertaken. Obvious reasons include no interest in revisiting a site, sites not being precisely enough described, sites having disappeared, etc. Among the few exceptions is a study by Powell (1966), reporting the maintenance of a patch of *Codium adhaerens*, a rare species in the British Isles, for at least 38 years, on the same two adjacent boulders.

VII. Biogeographical studies

Biodiversity monitoring can also refer to biogeographical studies which give pertinent information relative to correlations between seaweed distributions and environmental conditions, historical or evolutionary taxonomic affinities between geographically isolated floras, and phylogenetic relationships within any given taxon over its distributional range (Druehl and Foottit 1985).

The calculation of the degree of endemism in a particular flora gives valuable clues to the relative isolation of a region. However, the percentage of endemics recorded is often reflective of the activity of collectors in different parts of the world.

VIII. Seaweeds as biomonitors

Algal bioindicators and bioassay methods are very well suited for analyzing autoecological, as well as synecological problems, by combining physical, chemical, and biological measurements to glean relevant information for the management of coastal zones. Seaweeds present several intrinsic advantages as ecological indicators: 1) they are benthic and, therefore, can be used to characterize integrated environmental conditions at one location over time, 2) they are generally easy to collect in sufficient amounts from various habitats, and 3) they readily accumulate compounds present in seawater, making tissue analyses reliable indicators of water quality, avoiding the logistical difficulties often associated with representative and comparative samplings of seawater (Levine 1984). Without entering it, the reader should be reminded of the continuous debate about whether or not laboratory experiments give meaningful results, and whether or not these results can be extrapolated to the natural and more complex conditions at sea.

Seaweeds have been used as indicators of pollution at the community level. However, some criticism is also appropriate when analyzing these studies because of the great variability in time and spacial scales, and the frequent lack of reference samples (t_0). Thus it is not always easy to distinguish and separate what is due to natural processes in species distribution from other causes, especially when based on short-time investigations. Different stages of the life history of a species can also be affected differently by pollution. Furthermore, species diversity in itself is not necessarily a reliable estimator of water quality (Archibald 1972): the cleaner the water, the more extreme the environment, which can then induce low species diversity. As Round (1981) put it "pure water would not be a good medium for algal growth"! Moreover, mild pollution could have an enriching effect.

Growth, productivity, biomass, and reproduction/fitness measurements have frequently been used as laboratory or field biodetectors to evaluate levels of pollution (Levine 1984). Phaeophyceae (*Laminaria*, *Ascophyllum*, *Fucus*) are often the selected plants for biomonitoring or experiments because they are resistant enough for laboratory manipulations, yet sensitive enough to various levels of pollution. These seaweeds also have extended geographical distributions making broad-based comparisons possible, and they are ecologically and economically (phycocolloids, fertilizers, etc.) important.

Because primary, secondary, and tertiary treatments of sewage are very expensive, these practices are not widely used on a worldwide basis. This, in conjunction with land runoffs and rainfall, leads to local nutrient enrichment, most often due to elevated levels of nitrogen and phosphorus. That acts as a stimulant to growth of algae which can then become a nuisance for biological (depletion of oxygen), aesthetic, or recreational reasons. This phenomenon is called eutrophication. Littler and Murray (1975) suggested that sewage favors rapid colonizers of early-succession stages (Cyanobacteria, *Ulva*, corraline red algae). Burrows (1971) mentioned the possibility of physiological adaptation to sewage stress, and cautioned about the selection of some species as biological indicators. Excessive growth of mostly green seaweeds (*Ulva*, *Monostroma, Enteromorpha*, *Cladophora*, *Chaetomorpha, Valonia*), called "green tides", are reported more and more frequently from different parts of the world (Morand and Briand 1996). Regular "green tides" events are well known, for example, in Brittany (Briand 1988) and in the Venice Lagoon (Orlandini 1988).

The removal of excess nutrients from waste water effluents by seaweeds has been investigated several times at the pilot scale level but has never been applied at the industrial scale (Schramm 1991). In the mid-1970's, interest was triggered by the search for renewable bioenergies (methanisation, fermentation) in a period of oil crisis. Today, ever increasing reports of eutrophication may attract attention again to seaweeds as candidates for tertiary waste-water treatment. However, one has to be careful that this does not merely result in a shift of the problem: from wastes in water to wastes accumulated in seaweeds, without planned utilization of the raw material and, consequently, dumping it somewhere else! Presently, different uses of seaweeds are investigated: fertilizer, compost, fodder, bioenergy production/conversion (Morand *et al*. 1991), phycocolloids, fibers, vitamins, antibiotics, etc. For the food industry, quality-control thresholds have to be developed as seaweeds do not only accumulate nutrients but also other compounds, which can be potentially toxic at certain concentrations.

Seaweeds have also been thought of as biomonitors of nutrient loading from aquaculture activities and as one component of integrated aquaculture systems, by combining nutrient removal and production of economically valuable seaweeds. After a rapid expansion throughout the world, and locally in the Bay of Fundy, the aquaculture industry is starting to realize that each habitat can carry only a certain level of mono-activity, and that exceeding the carrying capacity can generate severe disturbances related to eutrophication (Phillips *et al*. 1985; Gowen and Bradbury 1987; Folke and Kautsky 1989). One emerging consequence of aquaculture activities is a significant loading of nutrients (especially dissolved phosphorus, nitrogen, and particulate material) in coastal waters (Beveridge 1987). Several countries (especially Norway, Sweden, Scotland, France, Italy, Chile, and Israel), where intensive aquaculture is already an established industry, are in the process of implementing restrictions on the amount of nutrients allowed to be discharged by fish farms, as excessive fertilization can significantly alter the quality of the surrounding benthos and waters (Håkanson *et al*. 1988). Nutrient-rich waters, in the vicinity of fish farms, also favour the growth of opportunistic annual algae, such as *Enteromorpha*, *Cladophora*, *Pilayella*, and *Porphyra*, which are causing severe biofouling of cages, and restricting water and nutrient circulation (Indergaard and Jensen 1983; Rönnberg *et al*. 1992). At the same time, a decline of economically valuable perennial algae (*Ascophyllum*, *Fucus*, *Laminaria*) has been recorded due to increased competition, decreased light penetration, and increased sedimentation of organic matter (Wallentinus 1981). Different methods have been used to try to minimize the effect of nutrient loading, such as reducing nutrients and their leaching from diets, and trapping or stabilizing of the faecal matter (Phillips *et al*. 1993). Another approach is to develop polyculture systems by integrating the culture of macroalgae and suspension-feeders to fish culture. The concept is far from "revolutionary"! Countries from Asia have been practicing it for centuries (Chan 1993). Interestingly, civilizations that have been most successful at developing integrated aquaculture systems are the ones that treat wastes as valuable resources and know the whole meaning of the word "recycling" because they have been living in closed systems for centuries, where everything has to be reusable,. Western countries are regularly "reinventing the wheel" (Ryther *et al*. 1978, Indergaard and Jensen 1983, Kautsky *et al*. 1996), culminating now in the use of such obfuscatory "buzz-words" as "ecological engineering for environmentally improved and sustainable aquaculture operations"! Seaweeds can use the excess nutrient supply, and other animal metabolic by-products, for growth (Chopin *et al*. 1990 a and b; Fujita *et al*. 1989), while providing a significant amount of needed oxygen for fish farms through photosynthetic activity (Wildish *et al*. 1993). Moreover, by selecting seaweeds of commercial value (for the food, textile, pharmaceutical, biotechnological, cosmetics, and other enterprises), additional profits can be realized by industry (Petrell *et al*. 1993). However, the determination to develop integrated aquaculture systems will only come about if there is a major change in the consumer's attitude related to eating products cultured on "wastes", and in political and economical reasoning by seeking sustainability, long-term profitability, and responsible management of coastal waters.

Seaweeds can be affected by oil spillage, including those created by tankers and oil-well blowouts. The most severe damages are generally observed for species located high on the shore of sheltered habitats because it could take several days, or weeks, before they are "washed" again, depending on the tidal rhythm of the locality (Floc'h and Diouris 1980). In the case of the Amoco Cadiz wreckage in 1978 off the coast of Brittany (France), the *Pelvetia canaliculata* and *Fucus spiralis* algal belts suffered extensive damage, and germlings of the first species were first noticed again a year and a half after the disturbance. The filamentous red alga *Rhodothamniella floridula* was replaced by the opportunistic green alga *Enteromorpha* sp. In the case of the Torrey Canyon spill in 1967 along the shores of Cornwall (United Kingdom), where dispersants were used massively, it took 7 years for the distribution of seaweeds to return to normal (Gerlach 1982). Oil spills can, however, also be "advantageous" for species lower on the shore and whose grazers/predators have been temporarily eliminated because they were more susceptible to the disturbance (Round 1981). A noticeable extension of the lower limit of the *Fucus vesiculosus* belt was the greatest modification in the zonation of intertidal algae one year after the Amoco Cadiz spill (Floc'h and Diouris 1980). There is also the less publicized, but chronic, low level pollution by oil hydrocarbons and their degradation products. They have been studied on *Porphyra* (Schramm 1972), *Laminaria*, and *Ascophyllum* (Bokn 1987) and showed an inhibition in the algal growth rate.

Because seaweeds act as bioaccumulators by concentrating compounds several orders of magnitude above ambient seawater levels, they have been used as coastal water pollution monitors for heavy metals, hydrocarbons, herbicides, pesticides, PCBs, antifouling compounds, radionuclides, nutrients (eutrophication), and numerous other compounds (Round 1981, Levine 1984, Lobban and Harrison 1994). In designing a research program, it should be clear that what is measured is the amount of biologically available pollutants, which is not the total amount of pollutants. Moreover, bioavailability can be highly species- or population-specific, and different results can be obtained from the same species depending on the environmental conditions of the collection site at a particular time, the part of the plant, and stage of life history sampled. The physiological aspects of uptake and accumulation by seaweeds, and the chemistry of the pollutants should also be clearly understood. Some large accumulations of metals can occur within the apparent free space between cells, without reaching the cellular compartments of plants (Higgins and Mackey 1987). Also, some metals can be associated with extracellular polymers of epiphytic bacteria rather than the seaweed under investigation (Holmes *et al*. 1991). Unfortunately, there is no standardization at the present time and, consequently, comparisons between studies can be a nightmare and lead to incorrect conclusions when environmental influences, and their interseasonal and interannual variabilities, are not appropriately separated from genetic and biological effects.

Bioaccumulator species have also been investigated for their potential mutagenic/carcinogenic properties (Levine 1984). However, a fundamental question remains: are mutagens produced endogenously or accumulated by seaweeds? The presence of naturally occurring halogenated compounds, especially in red algae (Fenical 1975), can preclude or reduce the monitoring value of these organisms. For this purpose, Chopin and Brillant (unpubl.) are presently analyzing PAHs levels in *Ascophyllum nodosum* and *Fucus vesiculosus*.

Thermal pollution (mostly from power plants and other industries using water for cooling purposes) can have deleterious or beneficial effects on seaweeds (Lobban and Harrison 1994). As is often the case, the definition of what has positive or negative effects involves some human judgement and, therefore, can lead to disagreement among the different stakeholders. Moreover, temperature tolerance cannot be considered in isolation, and relationships with other abiotic and biotic parameters should be investigated. For example, a chemical disturbance can be associated with thermal disturbance when chlorine and copper are used for fouling treatment.

Wood-processing industries release large quantities of effluent. There has been only one study (Hellenbrand 1978) of the effects of treated kraft pulp-mill effluent on *Chondrus crispus*, *Ascophyllum nodosum*, and *Fucus vesiculosus*. Plants were not adversely affected, with productivity increasing for all three species, probably due to the nutrient enrichment caused by the effluent.

IX. Emerging trends in algal systematics

To the dismay of proponents of morphology-based alpha-classification, more sophisticated and costly new powerful laboratory techniques have recently been developed in the field of systematics. Some will deplore that this makes field identification more difficult, restricting expertise to only a few specialists, and reducing the role of monitoring by increasing numbers of volunteer-run organizations.

The significance of chemotaxonomy in algae has been underlined regularly, mostly on the basis of the distribution of cell-wall polysaccharides in different groups (Stoloff and

Silva 1957, Yaphe 1959, McCandless 1978, Percival 1978, Craigie 1990, Chopin *et al*. 1990b, Chopin *et al*. 1994). Others have suggested the use of secondary metabolites in the systematics of algae, associated with the quest for new biologically active compounds and the understanding of phylogenetic relationships (Norris and Fenical 1985).

Features of cell structure, best revealed at the electron microscope level, provide some of the most distinguishing characteristics of the different groups of algae and also reflect the diversity of their phylogenetic origin. As more cytological features reveal multiple character states (*e.g.* pit connections/plugs in red algae), the systematic potential of these features is being increasingly realized and used (Pueschel 1990).

The concepts of species and speciation in marine algae (especially the Rhodophyceae) have been discussed by Rueness (1978), Mathieson *et al*. (1981), and Guiry (1992) in light of recent information obtained from hybridization studies. For example, in the extremely polymorphic *Chondrus crispus*, which has been puzzling phycologists for almost two centuries (Chopin *et al*. 1996b), the traditional morphological species concept has been largely supplanted by the biological species concept. Guiry (1992) classified *C. crispus* among the category of problematical taxa in which morphologically dissimilar plants can cross while some show various levels of genetic and ecological distinctness. Other macroalgae also display great phenotypic, or ecotypic, plasticity (Norton *et al*. 1982, Russell 1987, Kalvas and Kautsky 1993, Rietema 1993), and, in most studies, the extent to which the observed differences are genetically and/or environmentally controlled has never been clearly established. Hence a definitive species identification is not yet possible for some of the problematic taxa.

In recent years, insights into biological and phylogenetic relationships of algae at the levels of population, genus, species, and subspecies have been gained by the use of isozyme electrophoresis (Cheney 1985, Lindstrom and Cole 1992) and DNA characters. Molecular techniques that have been successfully applied include: 1) DNA-DNA hybridization (Bot *et al*. 1990); 2) analysis of restriction fragment length polymorphism (RFLP; Goff and Coleman 1988, Bird *et al*. 1990, Rice and Bird 1990, Adachi *et al*. 1994, Chopin *et al*. 1996b); 3) comparison of nucleotide sequences of genes and spacer regions (Steane *et al*. 1991, Bakker *et al*. 1992, Bird *et al*. 1992, Goff *et al*. 1994, Hommersand *et al*. 1994, Zechman *et al*. 1994, Chopin *et al*. 1996b); 4) random amplified polymorphic DNA (RAPD) analysis (Patwary *et al*. 1993); and 5) DNA fingerprinting (Coyer *et al*. 1994). The problem is to choose the appropriate molecular tools and markers for the desired level of resolution in the identification. One should also not forget that no relationship has yet been established between the evolutionary rate of sequence variation in DNA and the rates of morphological divergence and speciation. This raises the corollary question of when does divergence become sufficiently large to be significant and delineate one taxon from another. As pointed out by Bird *et al*. (1992), the taxonomic significance of molecular sequence divergence must be evaluated on a case-by-case basis, in concert with phenotype and reproductive compatibility.

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Appendix

Succession models

In the facilitation model (Connell and Slatyer 1977), succession begins with colonization by pioneer species following perturbation; the pioneer species make the environment suitable for later species until climax species become dominant and arrest succession. In the tolerance model, later successional species are successful whether earlier species have preceded them or not; they can tolerate other species because of their ability to grow at lower resource levels. In both the facilitation and tolerance models, earlier species are killed in competition with the later species. In the inhibition model, later species cannot grow to maturity in the presence of earlier colonists, that are removed by natural mortality, extreme physical conditions or the effects of herbivory.