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Micro- and macrodiversity in *rbcL* sequences in ambient phytoplankton populations from the southeastern Gulf of Mexico

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ABSTRACT: Ribulose-1,5-diphosphate carboxylase/oxygenase (RuBisCO) large subunit genes (*rbcL*) were obtained by amplification and cloning of 554 or 614 bp sequences of indigenous phytoplankton populations at 2 stations in the southeastern Gulf of Mexico. One station (Stn 4) was located in a low salinity, high chlorophyll plume (the 'Green River') which has previously been shown to contain elevated levels of Form IA *rbcL* mRNA while the other (Stn 7) was in oligotrophic, oceanic water. A diversity of *rbcL* sequences was obtained, spanning 3 of the 4 evolutionary clades of Form I RuBisCOs. Six nucleotide sequences obtained from Stn 4 were closely related (92 to 96% similar) to the Form IA-containing *Prochlorococcus* GP2. Flow cytometry and pigment analysis indicated that *Prochlorococcus* was abundant at this site. Other sequences found included a Form IB *rbcL* closely related to prasinophytes, and Form ID sequences related to prymnesiophytes, diatoms, and pelagophytes. One sequence was nearly identical to the pelagophyte, *Pelagomonas calceolata*. At Stn 7, sequences were obtained that were more deeply rooted, and less similar to *rbcLs* in existing databases (77 to 83% similar), and no Form IA *rbcLs* were detected. HPLC pigment signatures and flow cytometry data were consistent with the forms obtained by cloning. The similarity of the 6 *Prochlorococcus* GP-2-like sequences (93 to 98%) is consistent with the phenomenon of molecular microdiversity as found at other loci in marine (and other environmental) microorganisms.

KEY WORDS: *rbcL* gene sequences · Phylogeny · *Prochlorococcus* GP-2

INTRODUCTION

Photosynthetic carbon fixation in the world's oceans is catalyzed primarily by the enzyme ribulose-1,5-diphosphate carboxylase/oxygenase (RuBisCO; Raven 1995). A diversity of phytoplankton participate in this process, including the picoplankton (*Synechococcus*, *Prochlorococcus*, and picoeucaryotes) as well as larger micro-, nano- and net plankton. Analysis of diversity in natural phytoplankton populations has usually been done by pigment analysis (Tester et al. 1995, Bidigare & Ondrusk 1996, Peeken 1997), flow cytometry (Campbell et al. 1997, Urbach & Chisholm 1998), or microscopy. Molecular approaches are now being widely used to investigate issues of diversity in heterotrophic and autotrophic picoplankton populations. Molecular phylogeny using 16S rRNA genes has been successfully used to determine the identity of (or nearest relative of) DNA sequences in the marine and other environments (Giovanonni et al. 1990, Moyer et al. 1995, Ferris et al. 1996, Field et al. 1997, Rooney-Varga et al. 1997). The problem with this approach has been that it has been difficult to target groups that perform a physiological or biogeochemical function in the environment, because 16S genotyping only yields information on the relatedness of one organism to another. A gene which encodes for a critical environmental function in one organism may be absent in a closely related 16S genotype. The diversity of natural populations of *Synechococcus* and *Prochlorococcus* has also been successfully investigated using RNA polymerase genes (Palenik 1994, Ferris & Palenik 1998). By using bioge-
were a shallow (45 m deep) subsurface chlorophyll a (chl a) content and a shallow (45 m deep) subsurface chlorophyll maximum (SCM; Paul et al. 2000, in this issue). This low plume that had a high chlorophyll was included 3 and 35 m for Stn 4 and 3 m for Stn 7. Stn 4 at the sites indicated in Fig. 1. The depths sampled these populations.

Little is known concerning the diversity of rbcL genotypes in natural phytoplankton populations (Pichard et al. 1997). To this end, we have amplified, cloned and bi-directionally sequenced portions of the rbcL genes from 2 distinct environments in the southeastern Gulf of Mexico. Our results indicate the presence of genotypes in natural phytoplankton populations (Pichard et al. 1993). As the rbcL database grows, more consistent phylogenies that take into account such lateral transfer events can be constructed.

MATERIALS AND METHODS

Sampling sites. Samples were taken during a research cruise aboard the RV 'Pelican' in August of 1997 at the sites indicated in Fig. 1. The depths sampled included 3 and 35 m for Stn 4 and 3 m for Stn 7. Stn 4 was located in a low salinity (29 ppt surface water) plume that had a high chlorophyll a (chl a) content and a shallow (45 m deep) subsurface chlorophyll maximum (SCM; Paul et al. 2000, in this issue). This low salinity feature was believed to have originated from the estuaries and rivers in the northern Gulf of Mexico, and has been termed the 'Green River'. This station also had elevated levels of Form IA rbcL mRNA and Synechococcus cell counts in the surface waters (8.6 × 10⁴ cells ml⁻¹), maximal Prochlorococcus cell counts (1.4 × 10⁵ cells ml⁻¹) at 40 m depth, and maximal picoeucaryotes (2.3 × 10³ cells ml⁻¹) at the SCM. Maximal carbon fixation occurred in the surface (3 m depth) sample (Paul et al. 2000, this issue). Stn 7 was more typical of the stratified, oligotrophic waters found in the Gulf of Mexico (Pichard et al. 1997), with a SCM at 83 m, and near constant salinity (~36 ppt) with depth. Synechococcus was in the surface waters (2.22 × 10⁴ cells ml⁻¹), Prochlorococcus maximal abundance (1.83 × 10⁵ cells ml⁻¹) at 50 m, and picoeucaryotes at the SCM (2.76 × 10³ cells ml⁻¹). Stn 10 was sampled by SCUBA divers over a reef in the Dry Tortugas.

DNA sampling. Seawater samples (500 to 1000 ml) were filtered onto 25 mm, 0.45 µm polyvinylidene difluoride filters (Millipore Durapore), the filters placed into 2.2 ml microfuge tubes, and 1.0 ml of STE (0.1 M NaCl, 10 mM Tris-HCl, 1 mM EDTA, pH 8.0) added and the filters frozen on liquid nitrogen. Samples were stored until extraction at −20°C. The extraction of environmental rbcL DNA were performed by boiling lysis in STE containing 1% sodium dodecyl sulfate as previously described in Pichard et al. (1993).

PCR. Two sets of degenerate oligonucleotide primers were designed for PCR amplification of rbcL gene fragments. The nucleotide sequences of the Form ID primers, which amplified a 554 bp fragment of the rbcL gene consisted of: forward primer: GATGATGA(AG)AA-(CT)ATTAAACCT-3'. Reverse primer: ATTTTG(A/G/T)CCACAGTG(A/G/T)-ATACCA-3'. Nucleotide sequences of primers which amplified a 615 bp fragment of the Form IA and Form IB rbcL gene consisted of: forward primer: TCICGTG-(A/G)AACTA(C/T)GGTCG and reverse primer: GGCAT(AG)TGCCAIAAC(AG)TG(AG)AT. Extracted DNA from different sampling stations was resuspended in sterile water and 1 to 5 µl of DNA was used for amplification in a reaction mixture containing 50 pmol each of the appropriate primers, 2 µl of each deoxyribonucleoside triphosphate (final conc. 0.2 mM each), 10 µl of 10X reaction buffer (Promega Inc, Madison, WI), 6 µl 25 mM MgCl₂ and 3 U of Taq DNA polymerase (Promega Inc, Madison, WI) in a total volume of 100 µl. To prevent nonspecific amplification and primer-dimer formation, Taq Start antibodies were used according to the instructions supplied by the manufacturer (Clontech Laboratories Inc, Palo Alto, CA).

Cycle parameters were as follows: 3 min at 95°C; 35 cycles of 1 min at 95°C, 1 min at 52°C, and 1 min 30 s at 72°C. These cycles were followed by a 20 min incu-
bation at 72°C. The retrieved amplicons were analyzed by electrophoresis in 1.5% (wt/vol) agarose gels stained with fluorescent stain Hoechst 33258.

Cloning and variant screening of PCR amplification products. Fresh PCR products were purified (QIAquick PCR purification kit, Qiagen Inc., Valencia, CA) and TA cloned into pCR®2.1 vector (Invitrogen Corp., Carlsbad, CA) according to the protocols provided by the manufacturers. A total of 110 white colonies were selected for study, and 76 of these were shown to contain inserts of approximately the expected size. Plasmid DNA was isolated using a plasmid isolation kit (Qiagen Inc., Valencia, CA), digested with restriction enzyme EcoRI and screened for variation using denaturing gradient gel electrophoresis (DGGE). DGGE was performed with a vertical gel electrophoresis apparatus (Hoefer SE 600) as described previously (Muyzer et al. 1993). In total 76 EcoRI restricted clones were applied onto 6% (wt/vol) polyacrylamide gels containing 0.5x TAE (20 mM Tris acetate [pH 7.4], 10 mM sodium acetate, 0.5 mM Na2-EDTA) with different denaturing gradients ranging from 0 to 80% denaturant (100% denaturant corresponds to 7 M Urea and 40% [vol/vol] deionized formamide). The gels were electrophoresed for 12 h at 60°C and 65 V. After electrophoresis, the gels were stained with SYBR Green I nucleic acid stain (Molecular Probes Inc., Eugene, OR).

DNA sequencing and phylogenetic analysis. Plasmids containing PCR-amplified inserts were sequenced with an Applied Biosystems model 373 sequencer at the Sequencing Core Laboratory (University of Florida, Gainesville, FL).

Deduced amino acid sequences were aligned with Clustal W as provided by OMIGA 1.1 software (Oxford Molecular group, Oxford, UK) using a pairwise, weighted alignment method. The gap penalty was 50, while gap elongation penalty was set to 10. The alignment was visually inspected for obvious misalignments and was then exported to the MEGA 1.02 software (Kumar et al. 1993). MEGA was used to compute neighbor-joining trees applying gamma distribution as a distance method to correct for multiple hits. While different gamma parameters were explored the default value of 2 was applied in order to generate the trees (using TreeView [Page 1996]) in Figs. 2 & 3. Closest relatives to rbcL clones were obtained by using NCBI's sequence similarity search tool BLASTN 2.0.8 (Basic Local Alignment Search Tool; Altschul et al. 1997). GenBank accession numbers for rbcL sequences for the organisms used to build the trees in Figs. 2 & 3 are as follows:

- *Synechococcus* PCC7002, D13971; *Anabaena* sp., L02520; *Bathycoccus prasinus*, U30275; *Calyptryosphaera sphaeroidea*, D45842; *Chlorella ellipsoidea*, M20655; *Chrysochromulina hirta*, D45846; *Cryptomonas* sp., X62349; *Cylindrotheca* sp., M59080; *Ectococca similicullosus*, X52503; *Emiliania huxleyi*, D45845; *Heterosigma akashiwo*, X61918; *Hibberdia magna*, AF015572; *Hydrogenovibrio marinus*, D43622; *Mn*-oxidizing bacterium, L32182; *Nitrobasil vulgaris*, L22885; *Odonella sinensis*, Z67753; *Pavlova salina*, D45847; *Synechococcus* PCC6301, J01536; *Pelagococcus subviridis*, AF15580; *Pelagomonas calcoelata*, U98998; *Pleurochrysis carterae*, D11140; *Prochlorococcus GP2*, D21833; *Prochlorothrix hollandica*, X57359; *Rhodo- sphaeraeoides*, M64624; *Prochloron* sp., D21834; *Skeletonea costatum*, AF015569; *Spinacia oleracea*, V00168, J01443; *Thiobacillus* sp., D13539; *Synecho- coccus WH7803*, U46156; *Xanthobacter flavus*, X17252; *Gonyaulax polyedra*, L41063. rbcL sequences appearing in Fig. 3 from the Gulf of Mexico or cultures and published in our previous paper (Pichard et al. 1997) include: GOMst8 mRNA 5m, U93860; GOMst4 mRNA 80m, U93861; GOMst4 mRNA 50m, U93856; GOMst4 DNA 5m, U93290; GOMst4 DNA 25m, U93855; *Prochlorococcus* PAC1, U93858; *Prochlorococcus MED*, U93857; and *Synechococcus* WH78007, U93895. rbcL clone sequences obtained in this study can be accessed from GenBank using the following accession numbers: 10GH4, A179005; 10GH8, A179006; 10GY1, A179007; 4AH1, A179008; 4AH10, A179009; 4AH3, A179010; 4AH6, A179011; 4AH8, A179012; 4AH9, A179013; 4AY1, A179014; 4AY2, A179015; 4DCH1, A179016; 4DCH11, A179017; 4DCH12, A179018; 4DCH2, A179019; 4DCH6, A179020; 4DCH7, A179021; 4DCH9, A179022; 7HCY2, A179023; 7ACH3, A179024; 7ACH5, A179025; 7ACH9, A179026; 7ACY7, A179027.

RESULTS

Fig. 2 is a neighbor joining tree of deduced rbcL amino acid sequences from Genbank and those obtained from Stns 4, 7, and 10. The prefix number of the clone designation indicates the station from which it was obtained. For example, clone 4AY2 was obtained from Stn 4, depth 'A' or surface (3 m). Table 1 presents the most closely related sequence and the % similarity based upon deduced amino acid sequence and nucleotide sequence, rather than displaying a very large similarity table for all sequences. In total 6 Form IA rbcL sequences were cloned from Stn 4 that were most closely related to *Prochlorococcus* GP2. The degree of similarity of these clones to this organism based on inferred amino acid sequences ranged from 88% (clone 4DCH9) to 99% (clones 4DCH6, 4DCH11, and 4DCH12). Nucleotide similarities ranged from 93% (4DCH9) to 96% (4DCH12). Clones were isolated from
Fig. 2. Consensus tree obtained from a Neighbor Joining analysis of a deduced 178 amino acid-long alignment of 30 \( rbcL \) sequences from Genbank, representative of the 4 Form I \( rbcL \) clades, and 23 novel sequences obtained from Stns 4, 7, and 10. Five hundred bootstrap replicates were performed and values indicated on nodes show the resulting bootstrap percentages. The dinoflagellate Gonyaulax polyhedra was chosen as an outgroup, since it is a member of the Form II \( rbcL \) clade.

Both the surface waters and the 35 m depth. The clones were obtained by using both the cyano (Form IA/B) primers and the chromo (Form ID) primers. These clones were all relatively similar to each other (98 to 99% at the amino acid level, 94 to 99% at the nucleotide level) with the exception of 4DCH9, which had a lower similarity (88 to 89% at the amino acid level, and 93 to 99% at the nucleotide level).

Also present at Stn 4 were green algal sequences (Form IB \( rbcL \); Table 2) most closely related to prasinophytes. These ranged in similarity between 87 to 90% at the amino acid level and 80 to 91% at the nucleotide level to Bathycoccus prasinos.

Form ID (chromophytic algal) \( rbcL \) sequences were amplified from Stn 4 samples using both the cyano and chromophytic primers. Four such clones were in
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~Thirty-one of these sequences were from Genbank, 23 sequences are from the current study, and 8 sequences were published previously by us, 5 of which were from the Gulf of Mexico (Pichard et al. 1997). Other parameters of the analysis are as in Fig. 2.

The prymnesiophytes group (Fig. 2 and Table 1). The closest to a cultivated alga was that of 4AH8 which was 94 and 89% similar at the amino acid and nucleotide levels, respectively to *Chrysochromulina hirta*. Other prymnesiophyte-like clones included 4AH6, 4DCH2, and 4DCH7, which were similar to *Calyptosphaera sphaeroidea* and *Pleurochrysis carterea*. Also present in the surface waters was 1 diatom-like clone, 4AH1, which was 94% similar to *Skeletonema costatum*. This sequence showed a lesser similarity to the diatoms *Cylindrotheca* and *Odontella*.
Pelagophyte-like clones were also present at Stn 4. Clone 4DCH1 was identical to Pelagomonas calceolata showing that this organism is present in the Gulf of Mexico. A surface clone (4AH10) was 91% similar to *P. subviridis*.

Phylogenetic similarities of clones isolated from Stn 7 appear also in Fig. 2 and Table 2. No Form IA *rbcl* clones were found, even though hybridization occurred with the Form IA probe (Paul et al. 2000). One chlorophyte-like (Form IB) sequence, clone 7ACY7, was found at this station in the surface waters. This clone was not closely related to any *rbcl* in the database, being most similar to *Chlorella ellipsosioda* (88 and 77% similar at the nucleotide and amino acid levels, respectively). Several chlorophytes (Form ID) clones were obtained from Stn 7 as well, although these were all fairly deeply rooted amongst the existing *rbcl* sequences. Clone 7ACH3 was between the Form ID and Form IC *rbcl*s. The closest relative was *Hibberdia magna*, which is a heterokont alga, a chlorophytic autotrophic stramenopile, also known as a true chrysophyte (Daugs-

DISCUSSION

Twenty unique *rbcl* sequences were obtained from the water column at Stns 4 and 7 in the Gulf of Mexico and 3 additional sequences were obtained from the coral surface in the Dry Tortugas. Of the clones obtained at Stn 4, 6 were in the Form IA clade and most closely related to *Prochlorococcus GP2* (Shimada et al. 1997). Clones 7ACH9 and 7ACH5 were isolated from the surface waters of Stn 7 and were phylogenetically grouped between the pelagophytes and diatoms. Clone 7ACH9 was most likely a pelagophyte, 87 and 81% similar at the amino acid and nucleotide levels, respectively, to *Pelagococcus subviridis*. Clone 7ACH5 was more distantly related to the pelagophytes *P. subviridis* and *P. calceolata* (82 and 81% similar, respectively, at the amino acid level) than clone 7ACH9. Clone 7ACH5 showed a similar degree of relatedness to the diatoms *Skeletonema costatum* and *Odonella* as to the raphidophyte *Heterosigma akashiwo*.

Three clones were also obtained from the surface of corals in the Dry Tortugas. These included a green algal-like clone (10GY1) most closely related to the prasinophyte *Bathycoccus prasinos*, a diatom-like clone related to *Cylindrotheca* (10GH4; 93% similar), and a pelagophyte-like clone related to *Pelagococcus subviridis* (10GH8, 92% similar).

Table 1. Closest relatives to *rbcl* clones obtained from Stn 4

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<th>Depth</th>
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<th>Primer pair used</th>
<th>Relative</th>
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<th>%AA similarity</th>
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<td>98</td>
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*Prasinophyte; *pyrmenesiophytes; *pelagophyte; *diatoms

Table 2. Closest relatives to *rbcl* clones obtained from Stns 7 and 10

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*Green alga; *heterokont chrysophyte; *pelagophyte; *prasinophyte; *diatom
DGGE gel yet unique sequences. The lower levels of DGGE. For example, many of the clones obtained with genotypes or our capability to screen unique clones by amplification. 2000). We are not certain as to the efficiency of the surface and subsurface waters by direct WH7803 Form IA mada et al. 1995) but unfavorably with Prochlorococcus in this study is Part 1999, Partensky et al. 1999, West & Scanlan 1999). The gene sequences is that they have an overall low G+C content (average 36.8%; Partensky et al. 1999). The Form IA sequences is that they belong to a strain that has yet to be sequenced. This is unlikely in while the LL clade contains the Form IB A diversity of chromophytic (Saunders et al. 1995) rbcL sequences were found at Stn 4, including diatoms, prymnesiophytes, and pelagophytes. Of the prymnesiophytes, 1 was most closely related to Chrysochromulina hirta (4AHB), while the other clones fell clearly in the prymnesiophyte 'clade'. Prymnesiophytes are known to form a separate clade within the Form ID rbcL sequences distinct from diatoms, pelagophytes, red algae, and brown algae (Daugbjerg & Andersen 1997b). These algae, also known as haptophytes of the 'heterokont' chromophytic algae, are known to contain chl a and c, as well as the carotenoid 19'-hexanoyloxys fucoxanthin (Mejanelle et al. 1995). These pigments were found both in the surface and subsurface waters at Stns 4 and 7, with the highest concentrations at the SCM. These clones were found in waters with abundant picoeucaryotic cell counts as determined by flow cytometry (Paul et al. 2000). Prymnesiophytes have been described as important contributors to phytoplankton communities in the Southern Ocean (Peeken 1997) equatorial Pacific (Bidigare & Ondrusek 1996, Verity et al. 1996) and in the NW Mediterranean (Bustillos-Guzman et al. 1995).

The 4AH1 sequence fell clearly in the diatom clade. Only a few diatom rbcL sequences exist at this time (Daugbjerg & Anderson 1997a), and the sequence obtained was not identical to any in the database (87 to 90% similar at the nucleotide level). There were diatoms present in the surface water plume of Stn 4 as indicated by the presence of Fucoxanthin and chl c1 and c2 (Paul et al. 2000).

Pelagophyte sequences obtained at Stn 4 were related to Pelagococcus subviridis (clone 4AH10) and 1 (4DCH1) was identical to Pelagomonas calceolata (Andersen et al. 1993). This is compelling evidence that P.
_calceolata_ was a member of the phytoplankton in these waters. The presence of pelagophytes as components of the picoplankton at this station was also verified by detection of 19'-butanoyloxyfucoxanthin (Paul et al. 2000), a pigment found in pelagophytes (Biddigare & Ondrush 1996, Peeken 1997).

Unlike the clones obtained from Stn 4, the _rbcL_ sequences obtained from Stn 7 were not as closely related to existing DNA sequences. For example, the green alga Form IB clone 7ACY7 was related to both _Chlorella ellipsoidea_ (77%) and spinach (72%). The 7ACH3 clone was related to *Hibberida magna* (83%), a chrysophyte related to synumphytes, and somewhat between the Form IC and ID lineages (Daugbjerg & Andersen 1997a). Sequence 7ACH5 was between the pelagophytes (81% similar to _Pelagococcus subviridis_) and the raphidophytes (*Heterosigma akashiwo*, 82% similar). It may be that waters at Stn 7 were more oligotrophic than Stn 4, and contained species similar to true oceanic taxa, and perhaps not as easily cultivated or readily studied as those from Stn 4. Thus, there may be less oligotrophic oceanic taxa in the _rbcL_ database than those from coastal oceanic waters, which may contribute to the dissimilarity of the clones obtained at Stn 7 to those in the database.

We have looked for similarities between the current Gulf of Mexico clones and those published by us previously (Pichard et al. 1997), which appear in bold in Fig. 3. None of the previously obtained clones were closely related to those obtained in the current study. The lack of similarity may not be surprising. First, the primer sets used between the 2 studies were different, even though they targeted the same general area of the _rbcL_ gene (a ~350 bp overlap exists between the 2 amplicons). However, the primer sets designed in the current study are based upon much more sequence data than those designed in 1994 for the 1997 publication (Pichard et al. 1997). Secondly, the relative biases of the primers are unknown. Finally, the differences in sequences could be the result of variation of the phytoplankton populations in space and time in the Gulf of Mexico as would be expected.

Xu & Tabita (1996) took a similar approach to the isolation of _rbcL_ sequences from Lake Erie, using a primer set that we had previously designed. Diatom-like _rbcL_ sequences were obtained from subsurface samples while green algal-like sequences were found in the surface and subsurface waters (Xu & Tabita 1996).

The occurrence of very similar yet non-identical sequences, as observed for the _Prochlorococcus_ GP2-like sequences of Stn 4, has been termed `molecular microdiversity' (Fuhrman & Campbell 1998, Moore et al. 1998). In all these studies (including the present one) the term `diversity' is misleading, because inherent in diversity is an indication of the abundance of each of the `species' or genotypes present (Shannon & Weaver 1949). A better term for what has been measured in these types of studies may be `genotype richness', analogous to species richness, which is the total number of species present. However, the types of amplicons obtained are limited by primer biases, relative efficiency of amplification, and other factors.

We do not think that the `molecular microdiversity' found in this study is simply PCR error caused by misincorporation of nucleotides. Using a similar calculation as that of Scala & Kerkhoff (1999), 1 PCR error in 10^4 bases (a high misincorporation rate) would result in 99.99% similarity after 1 PCR cycle. If 35 PCR cycles occur, then the % similarity between a true and `corrupted' sequence would be 99.99 or 99.7%. Thus, clones that are >99.7% similar are considered identical. Because our clones ranged from 92 to 96% similar to 1 another, we feel that the microdiversity measured was real and not an artifact of PCR.

The microdiversity observed with the Form IA sequences seems to be a common occurrence in many oceans (Field et al. 1997). Scala & Kerkhoff (1999) measured diversity of the nitrous oxide synthetase gene (_nosZ_) which encodes the final step in denitrification. These investigators found similarities ranging from between 33 to 99% for clones from the sediments of the Atlantic and Pacific continental shelves. Ferris et al. (1996) found microdiversity in thermophilic _Synechococcus_ populations in a thermal spring microbial mat. Zehr & coworkers (1998) have observed both microdiversity and macrodiversity in the _nifH_ genes obtained from environmental samples, again with differences only being a few % between clones, yet greater than that caused by PCR. Both macro- and microdiversity has been observed in the _rpo_ locus in _Prochlorococcus_ and _Synechococcus_ (Palenik 1994, Palenik & Swift 1996, Ferris & Palenik 1998).

The issue of molecular microdiversity raises some interesting evolutionary and ecological questions. For example, to what advantage would it be to have a population genetically similar yet not identical (presumably not clonally derived) competing for the same resources? Hutchinson (1961) raised this issue to question phytoplankton diversity in his paper _Paradox of the Plankton_. That paper was dealing with what we would term `macrodiversity', or differing phyla, classes, orders, and genera in the phytoplankton in a somewhat homogeneous environment, the water column. However, the _Paradox of the Plankton_ is even more appropriate when considering molecular microdiver-
sity. Fuhrman & Campbell (1998) considered this issue in Prochlorococcus, and wondered if the small changes in sequence are simply genetic drift or microevolution in physiologically similar, clonal populations, or if it is the result of macroevolution of distinct populations, each with unique niches? Genetic drift in a culture is either neutral or results in replacement of the original genotype with one more fit for the culture conditions, not a widespread diversification of the loci in question. Perhaps constantly changing conditions, as per the ability of phytoplankton and bacteria in the subtropical North Atlantic, can lead to varying conditions favoring one geno-

var over the other. Molecular microevolution occurs in every loci thus far examined, and may be a method for adaptation to environmental conditions and evolution of successful genotypes.

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