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An inventory of scaled chrysophytes from North Carolina, USA, and their relationships to environmental variables

by

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with 6 figures and 4 tables

Abstract: The distributions of silica-scaled chrysophytes in 27 freshwater ponds from three primary regions located along the Atlantic Coastal Plain of North Carolina, USA, relative to chemical gradients are described. Phytoplankton, periphyton, and surface sediments from each of the 27 sites were collected in May and June of 2001 and later analyzed extensively with both scanning electron microscopy (SEM) and light microscopy (LM) for scaled chrysophytes. In addition, water samples were used to measure a suite of chemical characteristics, including specific conductivity, pH, alkalinity, total phosphorus, total nitrogen, chloride, sulfate and base cation concentrations. Overall, waterbodies included in this study are highly acidic, poorly buffered, and humic. We have identified thirty-six taxa of silica-scaled Chrysophyceae and Synurophyceae, 15 of which were present in 5 or more waterbodies. The most important species included *Synura sphagnicola*, *S. echinulata*, *S. petersenii*, *Mallomonas matvienkoae*, and *M. wujekii*, a species previously only reported from lakes in north-central Florida. The number of taxa found per lake ranged from 0 to 16 and observations include 17 new records for North Carolina, including several rarely reported species. Although floras in North Carolina ponds are species poor compared to other regions, they are unique and distinctive.

Key words: chrysophytes, North Carolina, Atlantic Coastal Plain, acidic habitats, SEM, *Mallomonas multiunca* var. *pocosinensis*.

Introduction

Scale-bearing Chrysophyceae and taxa in the Synurophyceae (hereafter referred to as the scaled chrysophytes), are freshwater planktonic flagellates composed of overlapping siliceous scales with species-specific designs. Many species of scaled chrysophytes repeatedly have been found to be restricted along various environmental gradients and as such, can serve as excellent bioindicators (Kristiansen 1986; Siver 1995). Because many species of scaled

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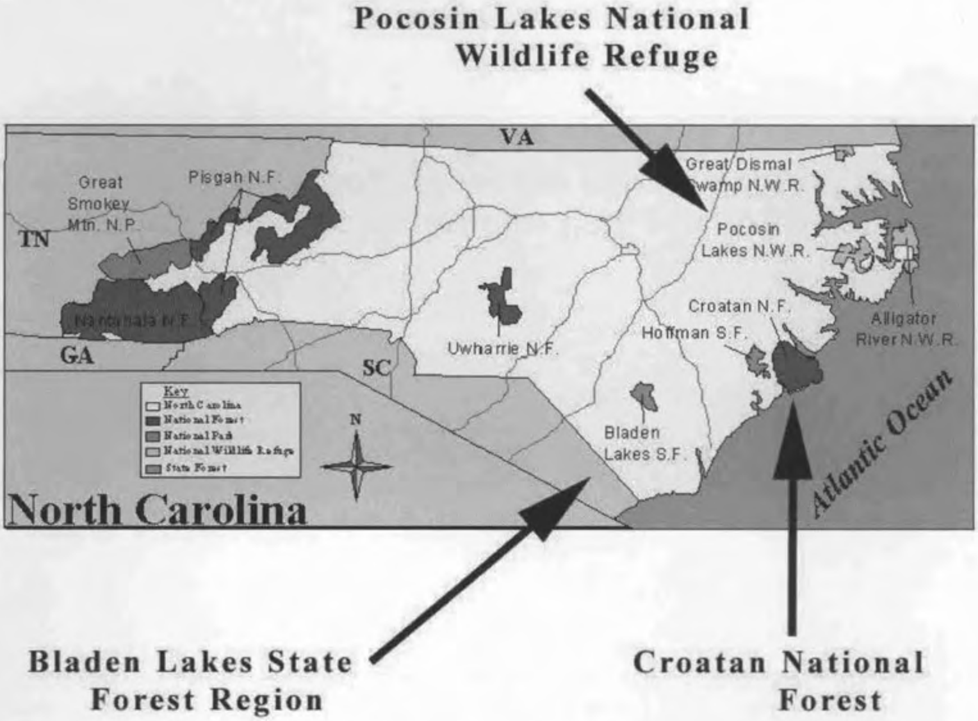

Fig. 1. Map of the North Carolina showing the locations of the 3 regions for our study lakes along the Atlantic Coastal Plain.

chrysophytes are excellent bioindicators and since their species-specific scales become archived in lake sediments, they have been utilized successfully in reconstructing historical lakewater conditions (Smol 1995). Scaled chrysophyte remains have been used to infer pH (e.g. Charles & Smol 1988; Siver & Hamer 1989; Cumming et al. 1992; Siver et al. 1999), specific conductance (Siver 1993), trophic related characteristics (Siver & Marsicano 1996), and the effects of landuse change on lake water chemistry (Siver et al. 1999).

In the state of North Carolina, recent studies of the scaled chrysophytes, have been limited to the central Piedmont (Wujek 2000) and western mountain (Wujek & Carter 2002) regions. Wujek (2000) studied 65 sites from the Piedmont Plateau of both North and South Carolina. The most frequently observed scaled chrysophytes of the Piedmont flora were *Mallomonas caudata*, *M. tonsurata*, *M. hamata*, and *M. crassisquama* and with the exception of one site, the pH ranged from 4.3 to 6.7. Wujek and Carter (2002) examined a smaller (n = 18) suite of lakes and ponds within the mountain region of North Carolina and found this area to be more diverse than the Piedmont region with 46 taxa recorded. Most frequently observed were *M. crassisquama*, *M. caudata*, and *M. akrokomos*, and the sites in this region had considerably higher pH values with a range of 5.6 to 9.2.

The primary purpose of this study is to describe and document the distribution and biodiversity of the scaled chrysophyte flora from 27 waterbodies in and around three regions situated along North Carolina's Atlantic Coastal Plain: the Pocosin Lakes National Wildlife Refuge, the Croatan National Forest, and the Bladen Lakes State Forest region (Fig. 1).

Methods

Twenty-seven relatively shallow waterbodies along the Atlantic Coastal Plain in North Carolina were sampled for plankton, periphyton and surface sediment samples in May and June 2001 (Fig. 1). Plankton samples were made with a 10 µm mesh net from the center of each waterbody. Representative periphyton samples were taken from microhabitats around the perimeter of each lake and stored in whirl-pak bags. Surface sediments were taken from the deep point of each lake using a Glew gravity corer (Glew 1988) and sectioned on site with a mechanical extruder (Glew 1989). Water samples for chemical analysis were taken at a depth of 1 m from the center of each waterbody. The Secchi disk depth and geographic coordinates were taken with a 20 cm black and white disk and a Trimble Geoexplorer GPS unit, respectively.

Chemical analyses followed the procedures of Ahrens & Siver (2000). Briefly, pH was measured on the same day of collection with a Fisher Acument 640-A pH meter. Conductivity and temperature were measured with a Hydrolab DataSonde 4A. Alkalinity was measured by the Gran titration method (Wetzel & Likens 1991) using Fisher reagent-grade 0.02N acid titrant. Chlorophyll-*a* was extracted in acetone and measured using the trichlorometric method (APHA 1985). Total phosphorus was determined using the stannous chloride-ammonium molybdate colorimetric assay after a persulfate digestion (APHA 1985). For total nitrogen, samples were first digested using the alkaline persulfate oxidation method (D'Elia 1977) and then analyzed using the N-(1-napthyl)-ethylenediamine dihydrochloride method (U.S. EPA method 353.2, 1983). Sulfate and chloride were estimated with anion chromatography (U.S. EPA 1983). Base cations were measured using flame atomic absorption spectroscopy with a Perkin Elmer 2380 spectrophotometer. Water color was determined by the platinum-cobalt method (APHA 1985). Data for all chemical parameters can be found at http://silicasecchidisk.conncoll.edu.

Approximately 1–2 ml of each plankton sample was air dried onto heavy duty aluminum foil the same day of collection. For the purposes of this study, aliquots of each periphyton sample were combined and prepared for SEM observation. The surface sediment (0–1 cm) samples and combined periphyton samples were oxidized with a sulfuric acid-potassium dichromate solution according to Marsicano & Siver (1993), and aliquots of each resulting slurry were air dried onto both glass coverslips and aluminum foil. The aluminum foil samples were used for observation with scanning electron microscopy (SEM) according to the procedures of Siver (1987). Essentially, samples were attached onto an aluminum stub with Apiezon ® wax, coated with a gold and palladium mixture for one minute with a Polaron model E5100 sputter coater and observed with a Leo 982 SEM or a Leo 435V SEM. Glass coverslips were mounted onto glass slides with Naphrax mounting medium.

All samples were used to identify, record and image scaled chrysophytes with SEM. Approximately 300 scales were enumerated for each sample using the surface sediment glass slide preparations with light microscopy (LM) after the sample was first thoroughly examined with SEM. In this manner identifications were confirmed with SEM. Percentages of scales for each sample can be found at our web site. For the purposes of this paper, we used the scale abundances to score each taxon as dominant, abundant, common, rare or very rare in each sample using the following criteria: Dominant = scale abundance > 39.9 %; Abundant = 20–39.9 %; Common= 5–19.9 %; Rare = 1–4.9 % and; Very Rare = <1 %. Taxa in the genera *Paraphysomonas* and *Spiniferomonas* were not included in the counts, but their presence and absence were noted at each site (Table 3).

We used the Sorensen Quotient (Novichkova-Ivanova 1980) to compare floras between waterbodies in our study with ones previously surveyed in North Carolina (Wujek 2000; Wujek & Carter 2002), and sites in the Ocala National Forest, Florida (Siver & Lott, in press).

Only genera in which actual relative abundances were able to be determined for this survey of Atlantic Coastal Plain sites of North Carolina (*Mallomonas, Synura, Chrysosphaerella,* and *Chrysodidymus*) were included in this determination. The number of waterbodies surveyed from each region varied and it should be noted that the Piedmont region sampled by Wujek (2000) included sites within both North Carolina (36) and South Carolina (29).

The Sorensen Quotient was calculated as follows:

$$K = (2c/(a + b)) \times 100$$

where c = the number of taxa common between the two regions being compared, a = the number of species in one region and, b = the number of species in the second region.

Study areas

Collecting sites included shallow wetlands, small ponds and lakes, large lakes and a series of canals (Fig. 2). The three primary regions sampled included a National Wildlife Refuge, a National Forest, and a series of lakes in and near State Parks. In terms of size, these sites ranged from unnamed depressions 0.4 hectares in size to over 6,475 hectares (Phelps Lake). In general, all waterbodies were quite shallow and most less than 3 meters deep. All sites were associated with pocosin or Carolina bay vegetation (see below); differences between the two vegetation types are minimal and controversial (Richardson et al. 1981). Please see http://silicasecchidisk.conncoll.edu for more details on all sites in this study.

Eleven waterbodies within or bordering the Pocosin National Wildlife Refuge (PNWR) were sampled including one pond, three lakes and seven canals. The pond and lakes are natural waterbodies whereas the canals are man-made structures built to reestablish water flow across the pocosin. Established in 1990, the PNWR is approximately 110,000 acres and two of its primary objectives include providing habitat for migratory waterfowl and protecting the unique pocosin vegetation that dominates the area. Pocosins, which essentially are wetlands or "raised bogs", are dominated by fire tolerant evergreen shrubs and scattered emergent trees (Christensen et al. 1981). The shrub layer is often dominated by plants such as *Cyrilla racemiflora* L., *Lyonia lucida* (Lam.) K. Koch, *Ilex glabra* (L.) Gray and *Zenobia pulverulenta* (Bartr. ex Willd.) Pollard, and *Pinus serotina* Michaux is the most common tree species (Christensen et al. 1981).

Drainage from the Pocosin National Wildlife Refuge is now accomplished by a series of canals that intersect the refuge itself and has been largely isolated from the surrounding agricultural areas through the construction of a series of earthen dams (Daniel 1981). The canals were originally put in near the turn of the century to drain the area for the farming and mining of the refuge's rich peat deposits; a large section of the refuge was also cleared. Currently, officials are working to restore the water flow over the Pocosins via culverts that would tie the canals together on either side of the dikes, which are necessary for access roads and fire control. Five of the canal sites are extremely humic, acid and are not influenced by runoff from agricultural fields. Two canals, Middle Nodwell and Seagoing, received direct runoff from agricultural fields via a small river and are significantly higher in pH and alkalinity (Table 1).

The Bladen Lakes State Forest region consists of ponds and lakes associated with Carolina bays; seven waterbodies from this region were sampled in this survey. Ingram and Otte (1981) note that there are over 2000 Carolina bays scattered over most of the coastal plain of the United States, with the concentration of them in Bladen County, North Carolina. Some may exist as far south as Florida and as far north as New Jersey (Ross 1987). Carolina bays are distinguished by being shallow, elliptical depressions with a standard northwest-southeast orientation (Ross 1987; Ingram & Otte 1981), and range in size from 1 to over 800 hectares (Richardson et al. 1981). These bays have a very controversial origin that has been debated

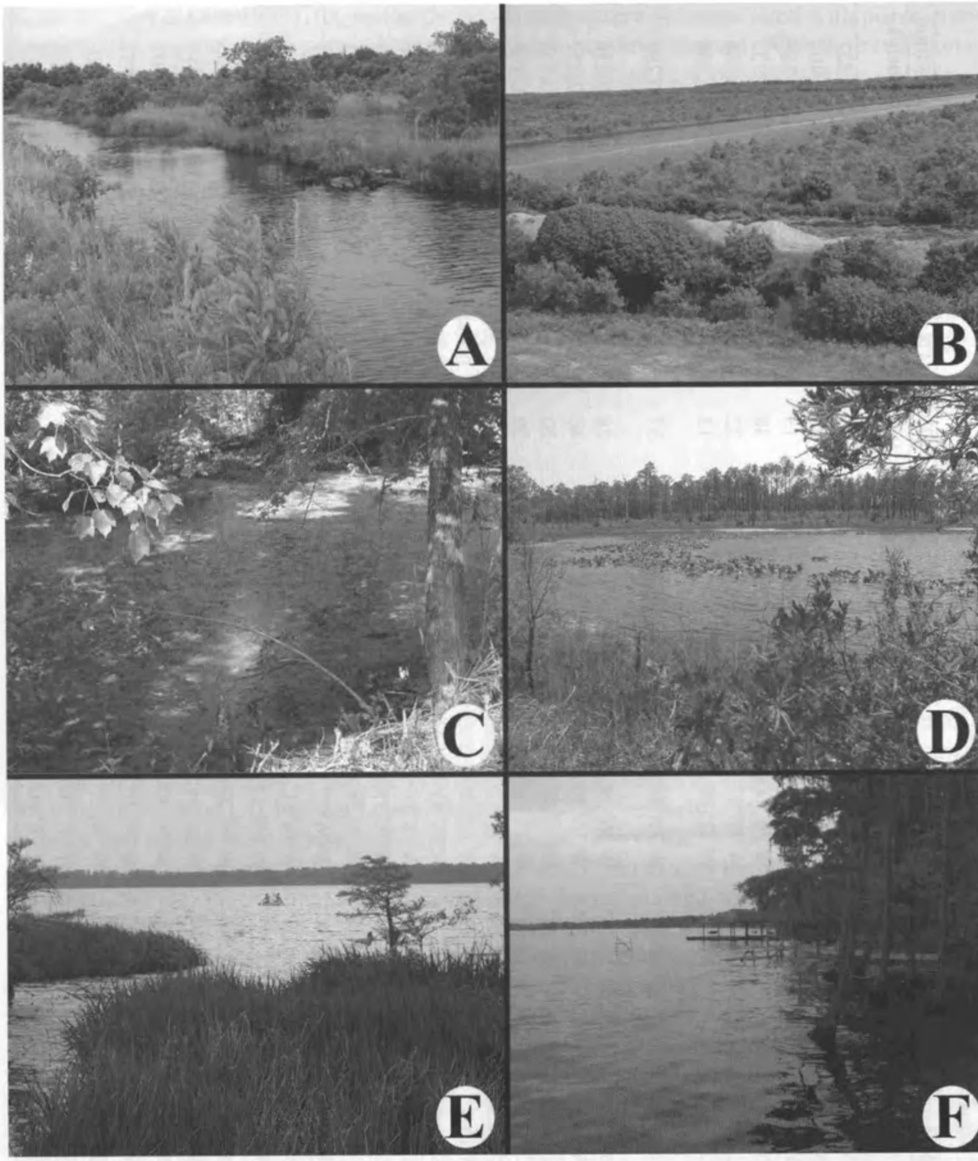

Fig. 2. Representative sites from this survey. (A) Clayton Canal - Pocosin NWR (B) Allen Road Canal – Pocosin NWR (C) Middle Nodwell Canal close-up - Pocosin NWR (D) Patsy Pond – Croatan National Forest (E) Great Lake – Croatan National Forest (F) White Lake – Bladen Lakes State Forest Region.

for over 50 years and no single theory has been acknowledged by scientists, although many have been proposed (Ross 1987, and references therein). The Bladen Lakes region consists of vegetation associated with Carolina bays which is similar in composition to pocosin vegetation (Richardson et al. 1981). Because the soils are comprised largely of woody peat and

Table 1. Physical and chemical data for 27 waterbodies along the Atlantic Coastal Plain of North Carolina.

Name	Code	Region	Latitude	Longitude	pH	SC	Color	TP	TN	CHL-a	Secchi	Sodium
					epi	uS/ cm	Pt-Co Units	(ug/L)	(mg/L)	ug/L	Meters	(meq/L)
Allen Rd Canal	ALC	Pocosin	N 35° 44' 13.82"	W 76°30' 50.83"	3.5	128	1665	49	2.120	15.8	0.14	0.227
Allen Rd Pond	ARP	Pocosin	N 35° 44' 15.89"	W 76°30' 55.36"	3.5	161	1375	80	2.572	56.1	0.12	0.404
Bay Tree Lake	BAY	Bladen	N 34° 40' 59.36"	W 78°24' 58.77"	4.6	68	23	13	0.412	9.7	0.99	0.388
Boerma	BOE	Pocosin	N 35° 44' 35.19"	W 76°29' 41.01"	3.5	121	1415	38	2.008	27.4	0.20	0.235
Catfish Lake	CAT	Croatan	N 34°55' 58.95"	W 77° 05' 16.98"	4.0	75	250	22	0.660	20.9	0.35	0.308
Catfish Waterfowl Imp. Middle	CWIM	Croatan	N 34° 57' 41.36"	W 77° 08' 31.60"	4.4	44	150	12	0.544	–2.0	0.91	0.268
Catfish Waterfowl Imp. West	CWIW	Croatan	N 34° 57' 40.87"	W 77° 08' 45.27"	4.7	53	492	37	1.612	41.1	Bottom	0.289
Clayton Canal	CLA	Pocosin	N 35° 44' 20.76"	W 76° 28' 38.73"	3.5	119	1250	28	1.743	16.7	0.22	0.238
Conman's Corner	CON	Pocosin	N 35° 44' 43.39"	W 76° 29' 36.09"	3.5	121	1500	46	2.036	18.3	0.19	0.253
Debbie's Pond	DEB	Croatan	N 34° 43' 14.40"	W 76°57' 56.30"	4.2	130	300	20	1.782	12.7	0.34	0.770
Great Lake	GRE	Croatan	N 34° 51' 34.44"	W 77°03' 07.67"	4.0	94	125	30	0.465	23.2	0.34	0.408
Hannah's Pond	HAN	Croatan	N 34° 43' 23.14"	W 76°57' 30.70"	4.2	71	335	28	1.398	32.5	0.30	0.344
Horseshoe Lake	HOR	Bladen	N 34° 48' 29.87"	W 78°39' 05.50"	4.0	49	192	7	0.554	6.4	1.13	0.182
Jessup Pond	JES	Bladen	N 34° 51' 46.30"	W 78°43' 46.74"	3.7	93	875	10	0.850	5.5	0.56	0.207
Jones Lake	JON	Bladen	N 34° 41' 02.21"	W 78°35' 50.51"	4.0	71	117	7	0.474	4.1	1.06	0.226
Kasia's Pond	KAS	Croatan	N 34° 43' 18.60"	W 76°57' 38.79"	4.5	82	150	17	0.866	–9.8	Bottom	0.523
Long Pond	LON	Croatan	N 34° 53' 53.62"	W 76°59' 47.82"	3.9	85	192	32	0.585	6.8	0.31	0.363
Middle Nodwell	MID	Pocosin	N 35° 47' 20.52"	W 76°17' 25.72"	6.4	140	1250	130	3.150	28.0	0.23	0.581
New Lake	NEW	Pocosin	N 35° 37' 26.09"	W 76°21' 10.67"	4.6	116	100	103	1.511	101.1	0.14	0.543
Patsy Pond	PAT	Croatan	N 34°43' 34.53"	W 76° 57' 35.87"	4.7	72	58	14	0.498	5.8	1.22	0.501
Phelps Lake	PHE	Pocosin	N 35°44' 52.39"	W 76° 29' 36.04"	4.7	137	1	4	0.088	3.6	Bottom	0.590
Pungo Lake	PUN	Pocosin	N 35°42' 40.69"	W 76° 34' 09.91"	4.9	124	540	368	3.155	105.6	0.02	0.511
Salters Lake	SAL	Bladen	N 34°41' 55.60"	W 78° 37' 35.98"	4.1	62	125	16	0.437	6.8	0.77	0.201
Seagoing	SEA	Pocosin	N 35°46' 18.33"	W 76° 15' 19.00"	6.7	257	750	83	1.631	25.5	0.37	0.737
Singletary	SIN	Bladen	N 34°35' 12.39"	W 78° 27' 00.43"	4.1	58	217	23	0.555	10.8	0.55	0.226
Western Harvest	WES	Pocosin	N 35°42' 32.46"	W 76° 20' 28.17"	3.8	112	1040	54	1.886	33.7	0.35	0.303
White Lake	WHI	Bladen	N 34°39' 17.69"	W 78° 30' 19.88"	4.8	62	2	6	0.084	4.1	Bottom	0.313

muck (Ingram & Otte 1981), the wetlands, ponds and waterways associated with pocosin and Carolina bay vegetation are poorly buffered and high in humic content. With the exception of Horseshoe and Jessup Ponds, sites were located within State Park boundaries.

Located along the eastern-central coast, the Croatan National Forest (64,345 hectares) contains another concentration of smaller Carolina bays situated in pocosin vegetation (Richardson et al. 1981). Nine sites were surveyed from this National Forest including 5 ponds, 2 lakes, and two shallow wetland sides adjacent to Catfish Lake. These two areas, Catfish Waterfowl Impoundment Middle (CWIM) and Catfish Waterfowl Impoundment West (CWIW), are actively managed to attract waterfowl. It should also be noted that three small bays neighboring Patsy Pond in the Croatan NF region lacked official names and we therefore designated then as Debbie's Pond, Hannah's Pond, and Kasia's Pond in order to easily distinguish them for our records (Table 1). These four sites will be referred to as the Patsy Pond complex and precise coordinates are provided in Table 1.

Results

Water chemistry

The majority of waterbodies were notably very low in pH, poorly buffered, and low in dissolved salts (Table 1). All but two of the lakes ranged in pH from 3.5 to 4.9, with 14 localities having a pH of 4 or less. Twenty-three of the lakes (85 %) lacked alkalinity (values < 0 μeq/L). Middle Nodwell and Seagoing, both from the PNWR, were the two exceptions with pH values of 6.4 and 6.7, and alkalinities of 705 and 2,028 μeq/L, respectively. Except for Seagoing (257 μS), all of the waterbodies were also relatively dilute with specific conductance values between 44–161 μS. Sodium was the dominant cation in all but Seagoing with a mean concentration of 0.38 meq/L, and mean concentrations of calcium, magnesium, and potassium were 0.16 meq/L, 0.11 meq/L, and 0.02 meq/L, respectively. Mean concentrations of chloride and sulfate were 0.31 meq/L and 0.20 meq/L, respectively, for all waterbodies.

Although our sites ranged from clearwater (1 Pt-Co Unit) to very highly colored (1,665 Pt-Co units), the majority of the sites contained richly humic-stained water (Table 1). Approximately half of the sites had values over 300 Pt-Co units, and with the exception of Phelps Lake, all sites from the PNWR sites had values over 1,000 Pt-Co units. Of the suite of 27 waterbodies, Phelps had the lowest color, TP and TN values at 1 Pt-Co unit, 4 μg/L, and 0.09 mg/L, respectively. Due to the high water color, the mean secchi disk depth was only 0.51 m with an overall range from 0.12 to 2m. Chlorophyll-*a* concentrations were relatively high, especially in the PNWR and Croatan regions (11 sites above 21 μg/L), with an overall range of < 1 to 106 μg/L. Total phosphorus concentrations ranged from 4 to 368 μg/L, and 63 % were higher than 20 μg/L; the nine highest values all belonged to sites in the PNWR. Total nitrogen ranged from 0.084 to 3.155 mg/L and again, the highest 7 values belonged to the PNWR region. Pungo Lake had the two highest values of TP and TN at 368 μg/L and 3.155 mg/L, respectively. The high chlorophyll-*a*, TP, and TN concentrations in the PNWR sites was due, in part, to high levels of particulate matter associated with the canal sites.

Scaled chrysophytes

A total of 36 taxa, representing five genera, were identified in the 27 study sites. The number of species per lake ranged from 0 to 16, with a mean of 7. The majority of the species belonged to the genera *Mallomonas* or *Synura*, accounting for 27 and 5 taxa, respectively. Tax-

Table 2. The number of occurrences and maximum abundances (%) for chrysophyte taxa found in 27 North Carolina waterbodies. "X" indicates that no relative abundances were determined but that the taxon was observed with SEM. An asterisk indicates a new record of the taxa for the state.

Taxon name	Number of occurrences	Maximum abundance
Chrysodidymus synuroideus Prowse	8	5.0
Mallomonas acaroides Perty var. *muskokana* Nicholls	9*	24.0
M. akrokomos Ruttner in Pascher		24.0
M. alpina Pascher & Ruttner	1*	0.2
M. asmundiae (Wujek & van der Veer) Nicholls	1	1.4
M. binocularis Siver	4*	10.8
M. caerula Siver	1*	1.0
M. calceolus Bradley	1*	0.6
M. canina Kristiansen	9*	20.9
M. caudata Ivanov	2	13.3
M. cristata Dürrschmidt	5	5.8
M. duerrschmidtiae Siver, Hamer & Kling	6*	24.7
M. favosa Nicholls	3*	54.7
M. hamata Asmund	2	7.8
M. insignis Penard	1*	1.3
M. lychenensis Conrad	1	1.9
M. mangofera Harris & Bradley	8	33.3
M. matvienkoae (Matv.) Asmund & Kristiansen	11	46.8
M. multiunca Asmund var. *pocosinensis* Siver	8*	89.7
M. ouradion Harris & Bradley	1*	0.3
M. paludosa Fott	4*	2.5
M. peronoides (Harris) Momeu & Péterfi var. *bangladeshica* (Takahashi & Hayakawa) Wujek & Timpano	1*	5.1
M. peronoides (Harris) Momeu & Péterfi var. *peronoides*	1	5.1
M. tonsurata Teiling em. Krieger	2	30.0
M. torquata Asmund & Cronberg f. *simplex* Nicholls	2*	18.7
M. transsylvanica Péterfi & Momeu	1	0.7
M. wujekii Siver	13*	100.0
Paraphysomonas takahashii Cronberg & Kristiansen	1	X
P. vestita (Stokes) De Saedeleer	8	X
Spiniferomonas takahashii Nicholls	2*	X
Sp. trioralis Takahashi	5	X
Synura echinulata Korsh.	15	82.8
S. petersenii Korsh.	14	27.0
S. petersenii f. *truttae* Siver	X*	X
S. sphagnicola Korsh.	20	50.6
S. spinosa Korsh.	5	3.7
S. uvella Stein em. Korsh.	4	43.7

onomic authorities for all taxa found in this survey are given in Table 2, and the relative abundances in Table 3.

Overall, the most common and/or abundant taxa observed in the North Carolina sites were *Synura sphagnicola* (Fig. 6G), *S. echinulata*, and *S. petersenii* (Figs 6E-F), found in 74 %, 56 %, and 52 % of the lakes, respectively. *Synura sphagnicola* represented a wide range of relative abundances scores between rare and dominant; in 6 lakes it represented at least 20 % of the scale assemblage. *Synura echinulata*, the second most important taxon was found in slightly fewer lakes than *S. sphagnicola*, but often at much higher percentages; in 3 lakes it was dominant. In addition, eight other species, *Mallomonas wujekii* (Fig. 6A), *M. matvienkoae* (Fig. 5A), *M. acaroides* var. *muskokana* (Fig. 3F), *M. canina* (Fig. 4A), *M. multiunca* var. *pocosinensis* (Fig. 5C), *M. mangofera* (Fig. 4G), *Chrysodidymus synuroideus* (Fig. 3A-B), and *Paraphysomonas vestita* (Fig. 6B), were reported from 30 % or more of the sites. Five taxa, *M. caudata* (Fig. 4B), *M. hamata* (Fig. 4F), *M. tonsurata*, *M. torquata* var. *simplex* (Fig. 5H), and *Spiniferomonas takahashii* (Fig. 6C), were observed in only two of the waterbodies and an additional 12 taxa were rare and recorded at only one site. The only 2 sites lacking any scales, Allen Road Pond and Phelps Lake, are neighboring sites from the PNWR region, but with very different chemical properties.

Mallomonas wujekii was the fourth most abundant species of this survey and in the case of two lakes, New and Catfish, it accounted for 100 % of the scale assemblage. *Mallomonas binocularis* was found in four waterbodies within the Croatan National Forest that were closely grouped together in the southernmost section of the forest; it was recorded as common in two of these sites. *Mallomonas caerula* was very rare, found only in Baytree Lake.

Recently described from the Atlantic Coastal Plain of North Carolina, *Mallomonas multiunca* var. *pocosinensis* (Siver 2003) was found in 8 waterbodies. This species is clearly an important member of the phytoplankton flora in these coastal sites, especially within the PNWR. It dominated the flora (i. e. was dominant) in four PNWR canals (Allen Road, Boerma, Clayton, and Conman's Corner) and one lake (Jessup) in the Bladen Lakes region (Table 3). Although found at it's highest abundances in the PNWR, it is significant to note that this species was recorded in all of the three regions examined in this survey. The waterbodies harboring *M. multiunca* var. *pocosinensis* were highly acidic (3.5 to 4.6 pH) and highly colored (150 to 1,665 Pt-Co Units).

In terms of taxa from the other genera represented in North Carolina's Atlantic Coastal Plain region, *Chrysodidymus synuroideus* was recorded in 8 study sites. The presence of *Paraphysomonas vestita* and *P. takahashi* was noted in 8 and 1 sites, respectively. In addition, only two species of the genus *Spiniferomonas*, which has been shown to be a common and often abundant genus in northern climates of North America (Nicholls 1981; Siver 1988), were observed. *Spiniferomonas trioralis* (Fig. 6D) was recorded in 5 of the North Carolina waterbodies and *Spiniferomonas takahashii* in only two of the sites.

The two alkaline sites within the PNWR that were directly impacted by agricultural runoff, Middle Nodwell and Seagoing, harbored a distinctly different chrysophyte flora relative to all other sites (Table 3). A small river that traverses agricultural fields empties directly into both of these canals, significantly altering the water chemistry (Table 1) and apparently the flora of these two canals. Middle Nodwell and Seagoing contained the largest populations of *Synura uvella* (Fig. 6H). Only Pungo lake, also from the PNWR, contained any other observations of the species. In addition, the only observations of *Mallomonas peronoides* var. *peronoides* (Fig. 5E-F) and *M. peronoides* var. *bangladeshica* (Fig. 5G), were in Seagoing where the two varieties were recorded as common (Table 3). *Mallomonas matvienkoae* and *Synura spinosa* were also common in Seagoing.

One taxon from Pungo Lake was difficult to identify based on isolated scales (Fig. 5B). We have referred to this scale as *Mallomonas* cf. *multisetigera*. Although these scales did not have

Table 3. Scaled chrysophyte observations from 27 North Carolina waterbodies arranged in order of increasing pH. VR = very rare; R = rare; C = common; A = abundant; D = dominant and X = noted in SEM observations. See text for details. Site Code designations correspond to those found in Table 1.

pH	3.49	3.53	3.53	3.53	3.54	3.71	3.75	3.91	3.95	3.98	4.02	4.04	4.06	4.07	4.15	4.24	4.43	4.50	4.55	4.59	4.65	4.70	4.71	4.77	4.90	6.35	6.74
Site Code	BOE	ARC	CLA	ALP	CON	JES	WES	LON	CAT	JON	GRE	HOR	SAL	SIN	DEB	HAN	CWIM	KAS	NEW	BAY	CWIW	PAT	PHE	WHI	PUN	MID	SEA
Chrysodidymus synuroideus													C		R	R		VR			R	R		R	C		
Mallomonas acaroides var. muskokana						A		C				C	C			C	C	C			R			A			
M. akrokomos																						R			R		VR
M. alpina																											VR
M. asmundiae																											R
M. binocularis															C	R		VR				C					
M. caerula																				R							
M. calceolus																									VR		
M. canina							C	VR				C				A	C	R		VR	C	R					
M. caudata																	VR			C							
M. cristata												R								R	R	C		R			
M. duerrschmidtiae					VR		C				R									VR		C		A			
M. favosa								D			C			VR													
M. hamata											R											C					
M. insignis																									R		
M. lychenensis																						R					
M. mangofera							R	C		VR			A	VR		VR		VR									VR
M. matvienkoae							C				R	R			C	C	A	R			D	C			C		C
M. multiunca var. pocosinensis	D	D	D		D	D						R					C				R						
M. ouradion																									VR		
M. paludosa			R									R						VR				R					
M. peronoides var. peronoides																											C
M. peronoides var. bangladeshica																											C
M. tonsurata																				A				A			
M. torquata f. simplex			C																						C		
M. transsylvanica																									VR		
M. wujekii							C	C	D	D	D	C	D	D					D	D	C	A			C		
Paraphysomonas takahashii								X																			
P. vestita	X	X	X		X										X						X				X		X
Spiniferomonas takahashii																						X		X			
Sp. trioralis								X														X		X	X		X
Synura echinulata						R	C				C	A	VR		D	C	C	D			C	A		C	A	D	A
S. petersenii	R		VR		VR	VR	C					C					A			VR	C	R		R	C	R	R
S. sphagnicola	D	C	C		A	R	A			R	C	A	R	VR	A	D	C	R			C	C		C		C	R
S. spinosa			VR		VR																R					R	C
S. uvella										VR															C	C	D
No. of Taxa per lake	4	3	7	0	6	5	8	7	1	4	7	10	6	4	6	8	8	9	1	8	12	16	0	10	14	5	14

the well formed papillae found on the shield and anterior submarginal ribs of this species (Siver 1991), there do appear several faint examples on the dome. It may be that the secondary layer was not fully completed as we have seen with other species in this survey, such as *M. wujekii*. In addition, the scattered large pores observed on the posterior flange of these specimens matches this taxon. Due to this uncertainty, we have not included this taxon in the final list of the scaled chrysophyte flora of this region.

Comparisons made with the Sorensen quotient

The Sorensen quotient was determined between sites in this study vs. several others, in order to indicate the degree of similarity of the respective scaled chrysophyte floras (Table 4). Sites sampled in this survey (Atlantic Coastal Plain) were found to be quite different from previous work in North Carolina's Piedmont (Wujek 2000) and Mountain regions (Wujek & Carter 2002), at 38 % and 24 %, respectively. Sorensen quotients between our Atlantic Coastal Plain sites and those in the Ocala National Forest, Florida (Siver & Lott, in press), were also determined and had a much higher similarity quotient (71 %) than the previously reported regions within the same state of North Carolina (Wujek 2000; Wujek & Carter 2002).

Discussion

From west to east, the state of North Carolina can be divided into the Mountain, Piedmont and Coastal Plain regions. Two recent surveys described the scaled chrysophyte flora from the Piedmont region of North (and South) Carolina (Wujek 2000), and from the Mountain region of North Carolina (Wujek & Carter 2002), and provide a means for us to make some preliminary comparisons between all three geologic zones.

In a suite of 65 waterbodies spread over the Piedmont zone of North and South Carolina, Wujek (2000) documented 40 taxa of scaled chrysophytes; the number of taxa per site ranged from 0 to 18. Although the pH ranged from 3.2 to 6.7 in the Piedmont waterbodies examined by Wujek (2000) study, only two of the sites had a pH of 4 or less, yielding a very different situation relative to the coastal plain sites examined in our study. The most frequently observed species recorded by Wujek (2000) were *Mallomonas caudata* (65 %), *Synura spinosa* (51 %), *S. petersenii* f. *petersenii* (45 %), *S. echinulata* (43 %), and *M. tonsurata* (37 %). In coastal sites from our study, *S. petersenii* and *S. echinulata* were also frequently observed, but *M. caudata* and *M. tonsurata*, two taxa with relatively high weighted mean pH values (Siver 1991), were very rare. Many taxa found to be common in our study sites including *Chrysodi-*

Table 4. Sorensen similarity quotient results. ACP-NC = Atlantic Coastal Plain, North Carolina (this study); MTN-NC = Mountain region, North Carolina (Wujek & Carter 2002); PIED-NC = Piedmont region, North Carolina (WUJEK 2000); ONF – FL = Ocala National Forest, Florida (Siver & Lott, in press). This Sorensen quotient was based only on genera in which relative abundances are determined using light microscopy (see text for details).

	ACP-NC	MTN-NC	PIED-NC	ONF-FL
ACP-NC	100	24	38	71
MTN-NC		100	69	40
PIED-NC			100	45
ONF-FL				100

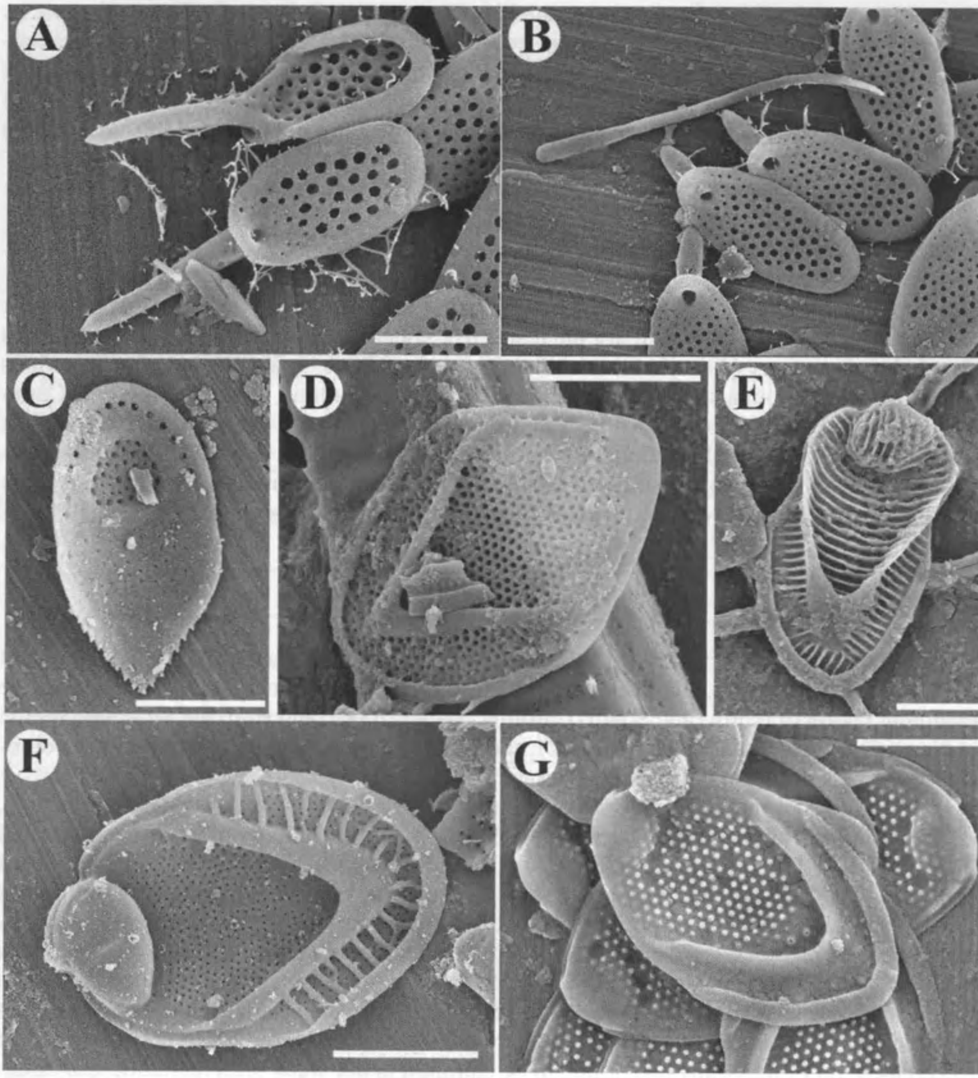

Fig. 3. (A) Two *Chrysodidymus synuroideus* scales. Scale bar = 1 µm. (B) Several *Chrysodidymus synuroideus* scales, including one tubular scale. Scale bar = 2 µm. (C) *Mallomonas akrokomos*. Scale bar = 1 µm. (D) *Mallomonas alpina*. Scale bar = 2 µm. (E) *Mallomonas asmundiae*. Scale bar = 2 µm. (F) *Mallomonas acaroides* var. *muskokana*. Scale bar = 2 µm. (G) *Mallomonas binocularis*. Scale bar = 1 µm.

dymus synuroideus, *M. canina*, *M. wujekii*, *M. multiunca* var. *pocosinensis* and *M. mangofera* (Table 3) were absent or reported in only one or two sites in the Piedmont study (Wujek 2000). In addition, *M. crassisquama* was absent from our survey which was the fourth most frequently observed organism in the Piedmont region (Wujek 2000). In summary, the scaled chrysophyte flora in our Coastal Plain sites is significantly different from that in the Piedmont waterbodies surveyed by Wujek (2000).

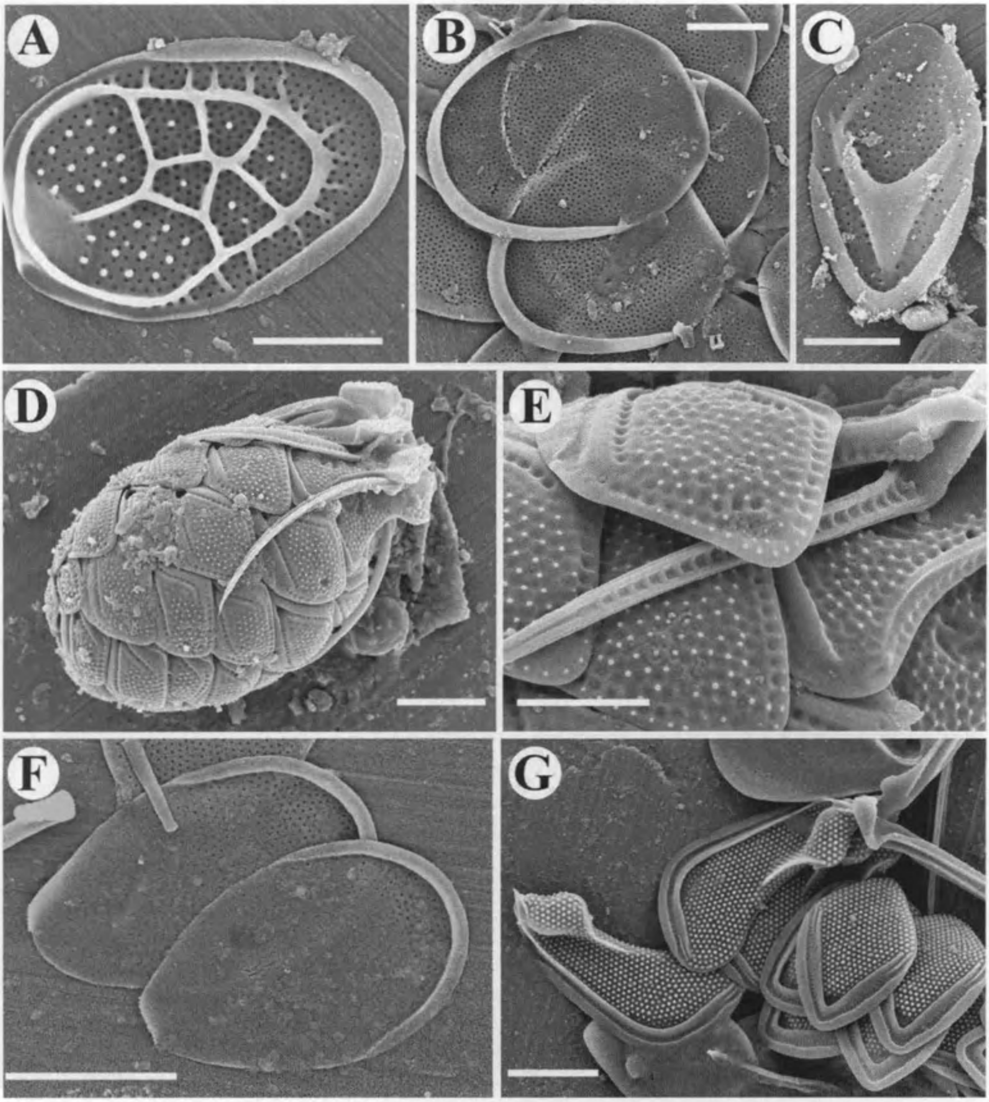

Fig. 4. (A) *Mallomonas canina*. Scale bar = 2 μm. (B) *Mallomonas caudata*. Scale bar = 2 μm. (C) *Mallomonas cristata*. Scale bar = 1 μm. (D) Whole cell of *Mallomonas favosa*. Scale bar = 2 μm. (E) Close-up of *Mallomonas favosa* cell. Scale bar = 1 μm. (F) Scales of *Mallomonas hamata*. Scale bar = 2 μm. (G) Group of scales from *Mallomonas mangofera*. Scale bar = 2 μm.

Wujek and Carter (2002) examined the flora in 18 sites situated within the Mountain region of North Carolina and documented 46 species of scaled chrysophytes, including 4 unidentified *Mallomonas* taxa. Although the range of pH in the Mountain region sites was 3.6 to 9.2, the majority of sites had a higher pH than our coastal plain waterbodies; 11 of the sites (61 %) had a pH above 6.5 pH. *Synura spinosa* (78 %), *M. crassisquama* (61 %), *S. petersenii* f. *petersenii* (61 %), *M. caudata* (56 %), and *S. echinulata* (56 %) were the five most observed spe-

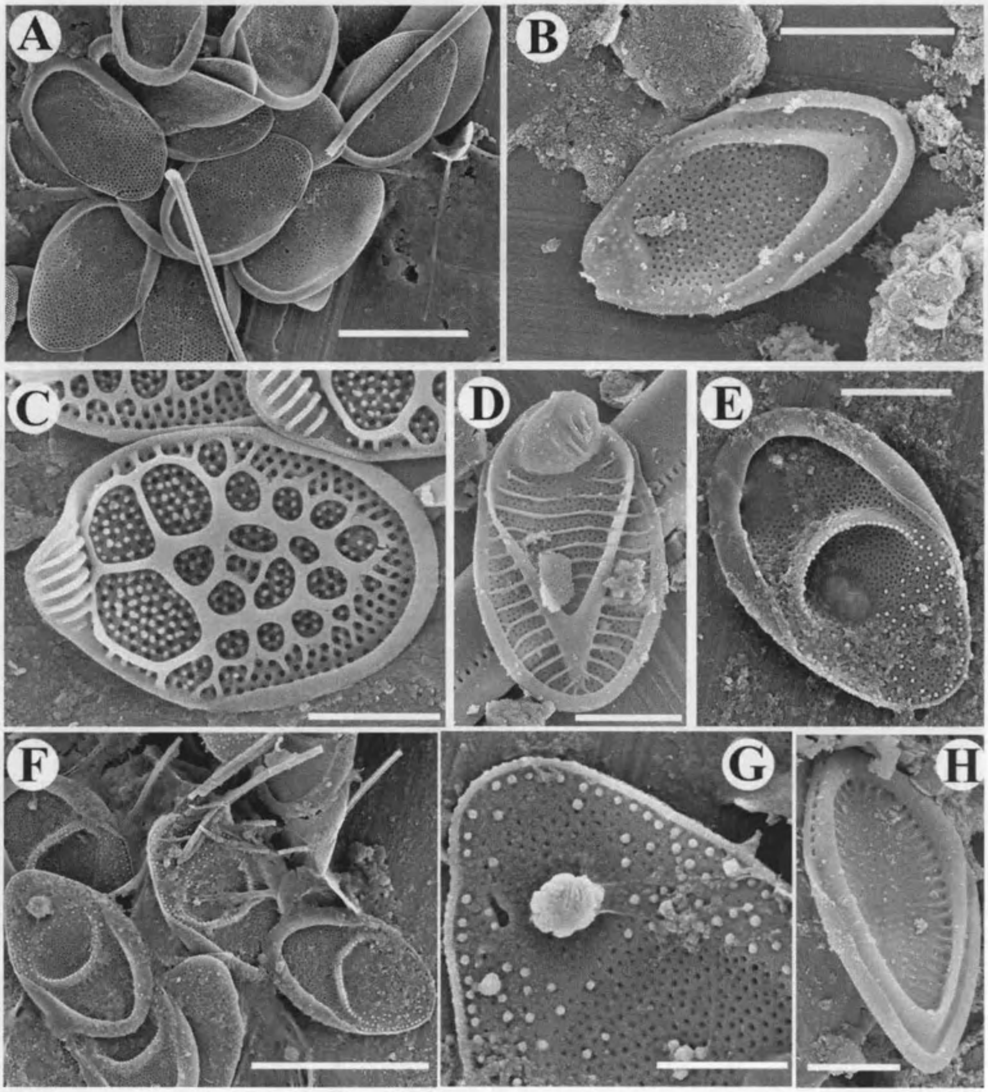

Fig. 5. (A) *Mallomonas matvienkoae* scales. Scale bar = 5 µm. (B) *Mallomonas* cf. *multisetigera*. Scale bar = 2 µm. (C) *Mallomonas multiunca* var. *pocosinensis*. Scale bar = 1 µm. (D) *Mallomonas paludosa*. Scale bar = 2 µm. (E) *Mallomonas peronoides*. Scale bar = 2 µm. (F) *Mallomonas peronoides* scales. Scale bar = 5 µm. (G) Close-up of ornament on *Mallomonas peronoides* var. *bangladeshica*. Scale bar = 1 µm. (H) *Mallomonas torquata* var. *simplex*. Scale bar = 2 µm.

cies in the Wujek and Carter study (2002). As noted above, *M. caudata* was very rare on the Coastal Plain and *M. crassisquama* was altogether absent. This is of particular interest since both of these taxa are among the most commonly reported species in studies from around the world (Siver & Skogstad 1988; Kristiansen 2002). It is likely that they are rare in these Coastal Plain sites because of the extremely low pH nature of these waterbodies. In general, both *M. caudata* and *M. crassisquama* are commonly distributed in waterbodies with significantly

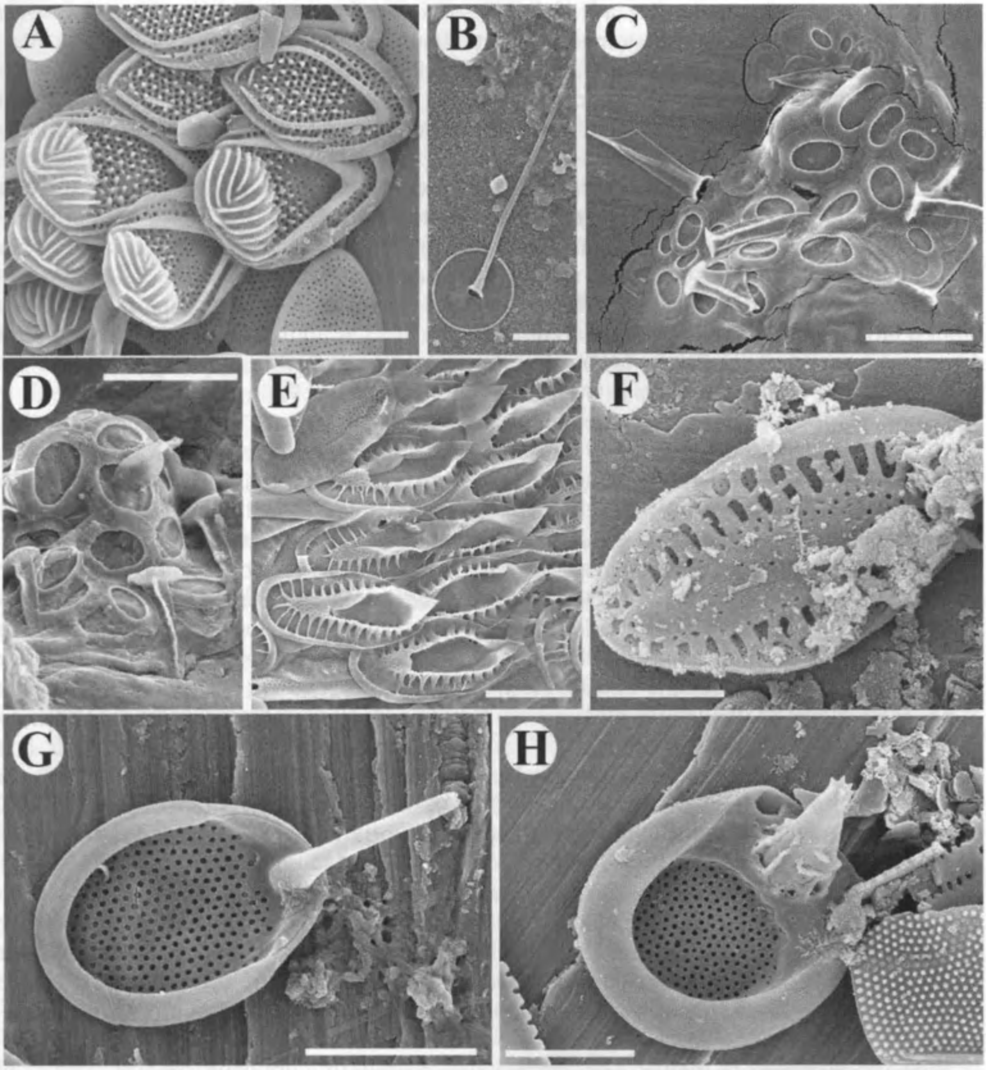

Fig. 6. (A) *Mallomonas wujekii* domed and domeless scales. Scale bar = 2 µm. (B) *Paraphysomonas vestita*. Scale bar = 1 µm. (C) *Spiniferomonas takahashii* scales. Scale bar = 2 µm. (D) *Spiniferomonas trioralis* scales. Scale bar = 2 µm. (E) *Synura petersenii* scales. Scale bar = 2 µm. (F) Scale of *Synura petersenii* f. *truttae*. Scale bar = 1 µm. (G) *Synura sphagnicola*. Scale bar = 2 µm. (H) *Synura uvella*. Scale bar = 2 µm.

higher pH (Siver 1991) than those along the North Carolina coast. Wujek and Carter (2002) also reported several observations of both *Chrysosphaerella longispina*, *C. brevispina*, and one site with *C. coronacircumspina*; it is noteworthy that the genus *Chrysosphaerella* was absent in all our coastal study lakes.

We further examined the degree of similarity in the scaled chrysophyte floras between our Coastal Plain sites and those situated in the Mountain and Piedmont regions using the Sorensen similarity quotient. We also made comparisons with the scaled chrysophyte flora from a suite of waterbodies in the Ocala National Forest in north-central Florida (Siver & Lott, in press). Sorensen quotients comparing the Coastal Plain flora with those of the Mountain (Wujek 2000) and Piedmont (Wujek & Carter 2002) regions were low at 24 % and 38 %, respectively. The low quotients support our conclusion that the scaled chrysophyte flora of the North Carolina Coastal Plain is distinctly different from the other major geologic zones within the state.

We also made comparisons between the scaled chrysophyte floras from the three North Carolina regions with that from a suite of waterbodies in the Ocala National Forest in north-central Florida, also part of the Atlantic Coastal Plain. The Sorensen quotients comparing the Ocala flora to those of the Mountain region (40 %) and the Piedmont zone (45 %) were also low, indicating very different floras. In contrast, the Sorensen quotient comparing the Ocala flora with the North Carolina Coastal Plain was high at 71 %, indicating the greater degree of similarity between these floras, despite being separated by a significantly larger distance. Interestingly, like the waterbodies in the North Carolina Coastal Plain, the lakes and ponds in the Ocala National Forest are also acidic, poorly buffered systems.

Based on our preliminary work in Ocala, North Carolina and other sites in Maryland and southern New Jersey (unpublished data), there appears to be a unique, possibly endemic, component of the scaled chrysophyte flora along the Atlantic Coastal Plain of North America. Six new taxa have recently been described from the Ocala sites (Siver 1994; 2002a; 2002b; Siver & Lott, in press). Of the new species, *M. wujekii* was an abundant and common taxon in the Ocala ponds, recorded in 73 % of the study sites. In our current study, we have documented *Mallomonas wujekii* populations in 48 % of the sites within the North Carolina Coastal Plain. Based on preliminary work, this taxon is also present in ponds along the more northern portion of the Atlantic Coastal Plain as far north as southern New Jersey, although it is not as abundant as in either Ocala or North Carolina. *Mallomonas wujekii* has not been reported in other works from the Atlantic Coastal Plain than ours (see Kristiansen 2002). It is not known from numerous sites surveyed in Connecticut (Siver 1991), Cape Cod (Siver 2001), northern New England (Siver & Lott 2000), the Adirondacks (Cumming et al. 1992) and eastern Canada (Nicholls 1982; 1988), supporting the idea that it is endemic to the Coastal Plain.

Two other newly described species from the Ocala region, *Mallomonas caerula* and *M. binocularis*, were also present in the North Carolina lakes, indicating that these species are also widely distributed over the Coastal Plain. *Mallomonas multiunca* var. *pocosinensis* is another recently described taxon (Siver 2003) that is abundant in a number of waterbodies associated with pocosins in North Carolina, but not known from any other studies worldwide (Kristiansen 2002).

With the exception of the two sites impacted by agricultural drainage, the waterbodies of the Pocosin National Wildlife Refuge sites are very acidic, high in total phosphorus and highly humic stained. The high total phosphorus concentrations is a direct result of the high level of particulate organic matter within the waterways. Six of the canals have pH values below 3.7, representing some of the most acidic sites surveyed for scaled chrysophytes. These six canals ranged between 3 to 8 species per site; *Mallomonas multiunca* var. *pocosinensis* and *Synura sphagnicola* were the most abundant in these systems. Other well known acidic taxa were observed as well including *M. canina*, *M. paludosa* (Fig. 5D), and *M. duerrschmidtiae*. In addition, several more cosmopolitan species including *Paraphysomonas vestita* (due to high organic loads) and *S. petersenii* were noted in a majority of these sites. Two adjacent sites in this region, Allen Road Pond and Phelps Lake, were the only waterbodies completely lacking scaled chrysophytes in this study (Table 3).

Of the three regions in this survey, the PNWR sites were unique because they included a series of 7 canals originally put in to drain the area for farming and mining (Daniel 1981).

These activities and the subsequent clearing of much of the land caused series declines in both the distribution and abundances of the natural pocosin vegetation (Richardson et al. 1981). Based on our data, these anthropogenic changes have also significantly changed the scaled chrysophyte flora as well.

The canal sites here can be grouped into two different categories based on the current water draining scenarios. Five of the canal sites, Boerma, Allen Road, Clayton, Conman's Corner, and Western Harvest, are extremely humic and acid (Table 1). Although the flora in the canals is low in terms of diversity, these five canal sites remain unaffected by agricultural runoff and are of specific interest due to their distinct flora. *Mallomonas acaroides* var. *muskokana* is absent from all sites in this region, and six rare taxa only found once, *M. alpina* (Fig. 3D), *M. asmundiae* (Fig. 3E), *M. calceolus*, *M. insignis*, *M. ouradion*, and *M. transsylvanica*, were also from this region (Table 3). Recently described originally from this same region, it is most important to note the presence of *Mallomonas multiunca* var. *pocosinensis* (Siver 2003). This variety accounted for between 48–90 % of the scale assemblage in 4 of these canal sites.

In contrast, the two most alkaline waterbodies of the survey, Middle Nodwell and Seagoing canals, are directly affected by the agricultural runoff which has significantly impacted the chemistry and resulted in a more alkaline flora. *Synura uvella* was an important part of the scale assemblage in both sites accounting for 13 % at Middle Nodwell and 44 % in Seagoing. This taxon was found to be common in one other PNWR site as well, but not in any other waterbody in this survey. In addition, the only populations of *M. peronoides* var. *peronoides* and *M. peronoides* var. *bangladeshica* were found in Seagoing, where it was common in both instances.

In conclusion, waterbodies along the Atlantic Coastal Plain of North Carolina contain a rich and diverse flora of scaled chrysophytes that is quite different from more inland sites within the state. We feel that it is necessary to protect these unique habitats in the future and to limit agricultural impacts, especially in the Pocosin National Wildlife Refuge, in order to preserve the unique flora of the region. This includes new species described solely from this region such as *Mallomonas multiunca* var. *pocosinensis* (Siver 2003) as well as others recently described from Florida's Atlantic Coastal Plain (Siver & Lott, in press). Further study along the Atlantic Coastal Plain is needed in order to document the ranges of these unique organisms.

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