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BURROWING MAYFLIES *(Hexagenia)*
as indicators of aquatic ecosystem health
at Sleeping Bear Dunes National Lakeshore, Michigan

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and William E. Phillips

Background

The National Parks Omnibus Management Act of 1998 encourages the development of programs to help protect natural resources throughout the National Park System by inventorying and monitoring those resources and establishing baseline information that can be used to provide status and trend information on their condition. Various studies have been conducted in recent years that contribute to the information base needed to protect and manage park resources, but the environmental status of most inland waters of the National Park System units in the Great Lakes Monitoring Network is still poorly known (Whitman et al. 2002) (fig. 1, page 42).

Major external threats to the inland waters of these parks include accelerated or "cultural" eutrophication caused by human activities that elevate, above natural or historic levels, the phosphorus in precipitation, surface runoff, and tributaries entering the parks. These elevated levels of phosphorus stimulate the excess production of algae, which removes oxygen from the water when the algae die, sink to the bottom, and decay. The effect of this excess algae production can be most severe in park inland lakes that stratify thermally in summer (see sidebar).

The effects of cultural eutrophication in Platte Lake (fig. 2, page 43), including excess algae blooms, and lowered water transparency, were the basis for legal actions brought by area property owners who wanted the nutrient loading to the lake from the Michigan Department of Natural Resources (MDNR) fish-rearing station to be reduced (Whelan 1999). In Loon Lake (see fig. 2), the effects of cultural eutrophication are not as apparent, suggesting that Platte Lake may be trapping much of the phosphorus carried by the river. The level of total phosphorus measured in Loon Lake in 1998 and 1999 (Whitman et al. 2002) was consistently low in water (0.03 to 0.04 parts per million), but varied seasonally and was much higher in lakebed sediments (80 to 478 parts per million), suggesting cultural eutrophication was occurring. The nitrogen:phosphorus ratio was 31.5 and very near the point (29.0) where the production of undesirable blue-green algae is favored over that of beneficial diatoms and green algae (Wetzel 1975); this further suggests that cultural eutrophication was occurring in Loon Lake. The absence of dissolved oxygen in the lake's deeper waters in August and September 1998 and 1999 (Whitman et al. 2002) is additional evidence that cultural eutrophication was occurring and suggests that phosphorus mobilization and release from the sediment during episodes of low dissolved oxygen might be sufficient to periodically lower the nitrogen:phosphorus ratio in water and trigger the production of blue-green algae. Earlier records describing dissolved oxygen levels in Loon Lake's bottom waters are not available, but Brown and Funk

> Elevated levels of phosphorus stimulate the excess production of algae, which removes oxygen from the water....

Thermal Stratification

Summer thermal stratification occurs when the sun warms the lake's surface and the warmer surface water becomes less dense than the colder, deeper water. These density differences cause three thermally distinct layers to form in the lake. The uppermost or surface water layer is uniformly warm; the mid-depth layer or thermocline is a zone of rapid transition where the temperature decreases rapidly as water depth increases; the deepest or bottom water layer is uniformly cold.

The density differences that cause the thermal stratification also inhibit mixing of the layers. The surface water layer, which is well mixed by the wind, is oxygen-rich. The dissolved oxygen concentration in the thermocline and bottom water layers reflects a balance between the oxygen demand by decaying algae and the dissolved-oxygen-bearing capacity of the water, which varies inversely with temperature. Thus, if the oxygen demand is high during summer thermal stratification, the dissolved oxygen concentration in the thermocline and bottom waters may become too low to support fish and invertebrate organisms, including *Hexagenia* nymphs.

(1940) reported that conditions in the bottom waters were adequate to support fish, including cisco *(Coregonus artedi)* and trout, which are cold-water fishes that typically would occupy these waters and require high levels of dissolved oxygen for survival. A more recent survey (Kelly and Price 1979) found only warm-water fishes were present. The apparent loss of resident ciscoes and trout suggests that low levels of dissolved oxygen developed between the early 1940s and the late 1970s and that cultural eutrophication was the responsible agent.

The present study describes the provisional use of burrowing mayflies (*Hexagenia* [Ephemeroptera: Ephemeridae]) as an indicator organism to assess and monitor the health of the Loon Lake and lower Platte River ecosystem within Sleeping Bear Dunes National Lakeshore, Michigan (figs. 1 and 2). The indicator approach (Edsall 2001, Environment Canada and the U.S. Environmental Protection Agency 2001) was promoted at international State-of-the-Lake Ecosystem Conferences in 1996, 1998, 2000, and 2002, and results from applying the indicator approach are being used to inform the United States and Canadian governments and the public about progress toward restoring and maintaining the chemical, physical, and biological integrity of the Great Lakes ecosystem, as required by the Great Lakes Water Quality Agreement (Environment Canada and the U.S. Environmental Protection Agency 2003). *Hexagenia* was selected as an indicator because it (1) was historically abundant in unpolluted, near-shore, soft-bottomed habitats throughout the Great Lakes; (2) was intolerant of and was extirpated by cultural eutrophication, which caused anoxic conditions in many of those habitats in the 1940s and 1950s; (3) has shown the ability to recover almost completely in one of those habitats, western Lake Erie, following nutrient reduction (Edsall et al. 1999); (4) is ecologically important in the food chain because it eats detritus and in turn is eaten prefentially by trout, bass, walleye, yellow perch, lake sturgeon, and other desirable food and game fish; and (5) has abundant, highly visible mating swarms of winged adults that, by their presence, can send a message to the public that the water body supporting the nymphal population is not suffering from the effects of cultural eutrophication.

Figure 1. National Park System units in the Great Lakes Monitoring Network. The study area is circled.

Methods

We conducted this study in Loon and Platte Lakes in the Platte River drainage and in two "reference" areas—Crystal Lake and Frankfort Harbor (Betsie Lake)—in the adjacent Betsie River drainage (fig. 2).

Sampling and measurements were made from a 17-foot-long (5.2 m) boat powered by a small outboard motor and equipped with a depth sounder, which continuously reported water depth to the nearest 0.1 foot (4.0 cm). We used a Petite Ponar grab sampler with a 0.25-square-foot (2.0 cm^2) jaw opening to collect *Hexagenia* nymphs burrowed in the lakebed substrate. We collected at least two grab samples with the Petite Ponar at each station where the first grab sample revealed that the substrate was suitable for *Hexagenia* nymphs. Suitable substrate for *Hexagenia* is typically soft enough to permit the nymphs to burrow in it and cohesive enough to prevent the burrow from collapsing (Wright and Mattice 1981). In the present study, suitable substrates were mud or mud and fine sand. Each grab sample with suitable substrate was dumped into a sieving bucket in which the bucket bottom had been replaced with one-eighth-inch mesh hardware cloth. The sediment portion of the sample was washed through the hardware cloth by partly submerging the bucket alongside the boat and moving it up and down several times. The nymphs retained in the bucket were counted and released.

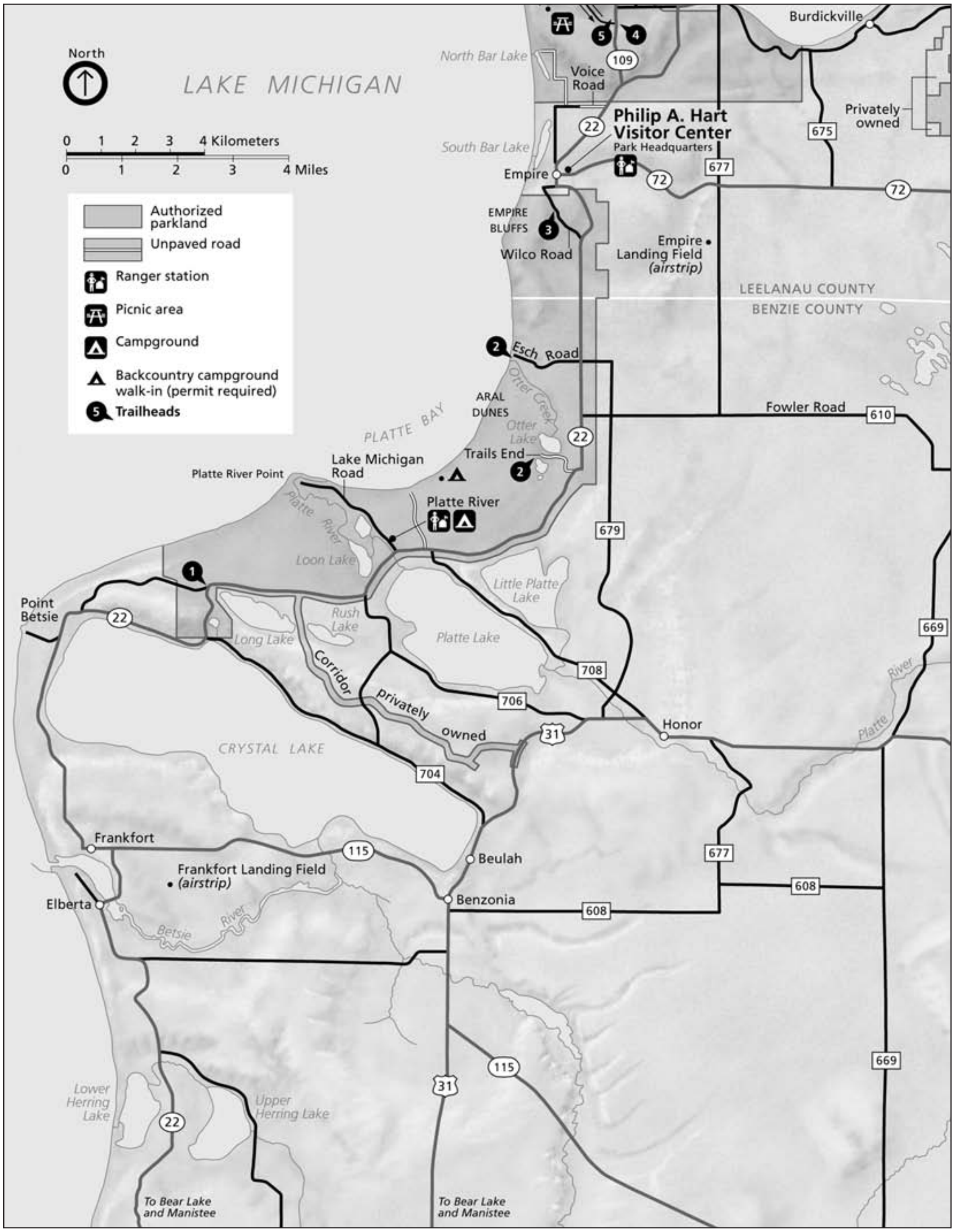

Figure 2. The study area, including portions of Sleeping Bear Dunes National Lakeshore, showing the Platte and Betsie Rivers, Loon, Platte, and Crystal Lakes, and Frankfort Harbor.

In Loon, Platte, and Crystal Lakes we collected Petite Ponar grab samples over a range of depths extending from the shallow, near-shore waters at depths of 10 to 20 feet (3.1 to 6.1 m), toward the offshore waters at depths of 37 to 49 feet (11.3 to 14.9 m) (table 1, page 44).

Sampling was conducted around the perimeter of Loon Lake, near the outlet of Platte Lake, and at the eastern end of Crystal Lake. In Frankfort Harbor, we sampled at a depth of 5 feet (1.5 m) near the mouth of the Betsie River and at 20 feet (6.1 m) at the eastern end of the navigation channel. We attempted to sample *Hexagenia* in Little Platte Lake and the lower Platte River below Loon Lake, but the substrate was sand or flocculent marl-like material, which was unsuitable for *Hexagenia*. We used a YSI Model 55 dissolved oxygen and temperature meter with a 50-foot (15.3-m) cable connecting the meter to its sensing probe to measure temperature to the nearest 0.1°F (0.06°C) and dissolved oxygen to the nearest 0.1 parts per million. The sensing probe was attached to a weighted line with 1-foot (0.3-m) markings, lowered to the bottom, and then retrieved to preselected depth intervals to provide data that would permit construction of dissolved oxygen and temperature profiles for each water body. Profiles extended from the surface of the water to depths of 42 to 50 feet (12.8 to 15.3 m) in Loon, Platte, and Crystal Lakes and to 20 feet (6.1 m) in Frankfort Harbor. The dissolved oxygen and temperature data for each water body were collected near the deepest site sampled with the Petite Ponar grab. A Garmin GSPMAP 76 chart-plotting global positioning system was used to record sample and data collection locations to the nearest 0.1 second.

The protocol for using *Hexagenia* as an indicator of ecosystem health (Edsall 2001) specifies sampling the nymphal population in the spring before the older, mature nymphs—which are the major biomass component of the population—emerge as winged subadults in early summer. Unfortunately, logistical constraints in 2002 prevented us from sampling until 24–26 July. As a result, we simply counted the nymphs we collected in each sample and did not attempt to obtain biomass data from them. This approach allowed us to describe the general distribution of the nymphal population and to examine the potential for using *Hexagenia* as an indicator of ecosystem health in the study area, but did not provide biomass data that could be used for trend monitoring following the protocol in Edsall (2001).

Results and discussion

Sampling with the Petite Ponar grab for *Hexagenia* nymphs in Loon, Platte, and Crystal Lakes revealed coarse and fine sand substrates extended from the shoreline out to depths of between 10 and 20 feet (3.1 and 6.1 m) in Loon Lake, 20 and 25 feet (6.1 and 7.6 m) in Platte Lake, and 14 and 17 feet (4.3 and 5.2 m) in Crystal Lake (table 1). Mud and fine sand was the substrate at 20 to 42 feet (6.1 to 12.8 m) in Loon Lake and 25 to 49 feet (7.6 to 14.9 m) in Platte Lake; mud was the substrate at 5 and 20 feet (1.5 and 6.1 m) in Frankfort Harbor. Nymphs were collected only from mud or mud and sand substrates, but were absent from mud and fine sand substrates at 30 to 42 feet (9.2 to 12.8 m) in Loon Lake and at 36 to 49 feet (11.0 to 14.9 m) in Platte Lake.

Table 1. Water depth, substrate, and catch-effort data for *Hexagenia* nymphs in Loon, Platte, and Crystal Lakes, and Frankfort Harbor, 24–26 July 2002

Location	Water depth (ft)	Substrate type	No. grab samples	No. nymphs
Loon Lake	10	Coarse and fine sand and clay	3	0
	20	Mud and fine sand[a]	5	3
	30	Mud and fine sand[a]	6	0
	40	Mud and fine sand[a]	3	0
	42	Mud and fine sand[a]	2	0
Platte Lake	20	Coarse sand and small shells (snails and fingernail clams)	2	0
	25	Mud and fine sand[a]	2	6
	36	Mud and fine sand[a]	2	0
	49	Mud and fine sand[a]	2	0
Crystal Lake	14	Coarse sand	1	0
	17	Mud and fine sand[a]	2	7
	20	Mud[a]	2	9
	25	Mud[a]	2	8
	29	Mud[a]	2	1
	37	Mud[a]	2	1
Frankfort Harbor	5	Mud[a]	2	10
	20	Mud[a]	2	2

[a]Substrate suitable for habitation by nymphs.

We collected no large, mature nymphs in Loon and Platte Lakes, indicating emergence probably had already occurred there. While sampling in Crystal Lake, we found windrows of floating *Hexagenia* exuvia (the outer body covering that nymphs shed at the surface of the water as they emerge as winged insects), indicating that an emergence had occurred during the previous evening. In Frankfort Harbor we collected several large, mature nymphs with black wing cases, indicating that some of the population there had not yet emerged. These observations indicate that sampling to establish trend information for the *Hexagenia* populations in the study area should be done in June when both density and biomass data can be collected as described in Edsall (2001).

The waters of Loon, Platte, and Crystal Lakes were strongly thermally stratified during our study (fig. 3). Surface temperatures were similar in all three lakes (74.5 to 75.7°F; 23.6 to 24.3°C) and the thermocline extended from about (slightly deeper than) 20 feet (6.1 m) to about 40 feet (12.2 m) in Loon Lake, about 25 to 40 feet (7.6 to 12.2 m) in Platte Lake, and about 30 to 45 feet (9.2 to 13.7 m) in Crystal Lake. The temperature in the surface layer immediately above the thermocline was 70.3°F (21.3°C) in Loon Lake, 74.3°F (23.5°C) in Platte Lake, and 75.2°F (24.0°C) in Crystal Lake. The waters of Frankfort Harbor were also strongly thermally stratified, but the warm surface layer seen in Loon, Platte, and Crystal Lakes was absent and the harbor's water temperatures were similar to or lower than those within the thermocline in Loon, Platte, and Crystal Lakes. The temperature in Frankfort Harbor declined almost linearly from 66.4°F (19.1°C) at the surface to 64.1°F (17.8°C) at 5 feet (1.5 m) and 47.5°F (8.6°C) at 20 feet (6.1 m). The absence of a layer of warm surface water probably reflected the direct connection of the harbor with Lake Michigan and the flushing of the harbor by a wind-driven

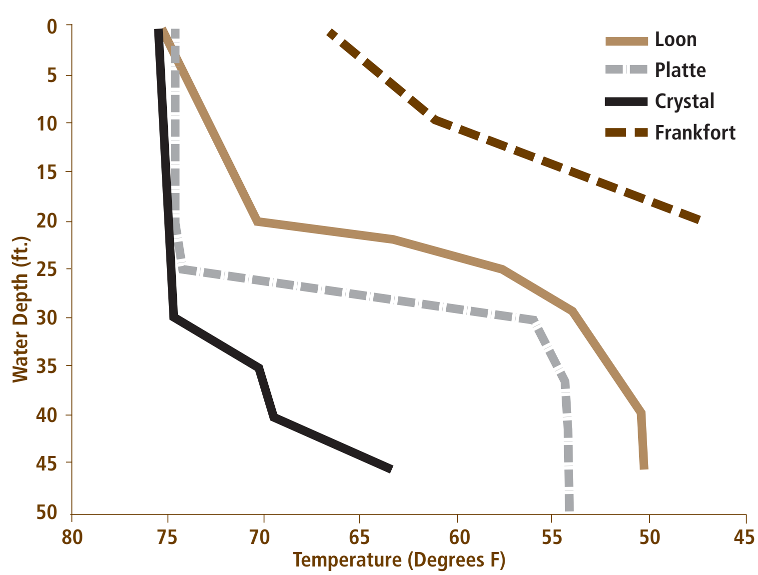

Figure 3. Temperature–water-depth profiles in Loon, Platte, and Crystal Lakes and Frankfort Harbor, 24–26 July 2002.

mass of cold Lake Michigan water. *Hexagenia* nymphs were only collected immediately above the thermocline in Loon and Platte Lakes, immediately above and within the thermocline in Crystal Lake, and only within the thermocline in Frankfort Harbor. The temperatures where nymphs were collected were 70.3°F (21.3°C) in Loon Lake, 74.3°F (23.5°C) in Platte Lake, 75.2 to 54.1°F (24.0 to 12.3°C) in Crystal Lake, and 64.1 to 47.5°F (17.8 to 18.6°C) in Frankfort Harbor.

In Loon and Platte Lakes, the dissolved oxygen concentration was 7.3 and 7.5 parts per million, respectively, at the surface, 7.5 parts per million immediately above the thermocline, and 0.6 and 2.8 parts per million, respectively, at the bottom of the thermocline (fig. 4).

In Crystal Lake, the dissolved oxygen concentration increased from 7.9 parts per million at the surface to 8.0 parts per million just above the thermocline, to 11.5 parts per million at 45 feet (13.7 m). In Frankfort Harbor, the dissolved oxygen concentration increased with depth, from 8.9 parts per million at 5 feet (1.5 m) to 11.8 parts per million at 20 feet (6.1 m). Nymphs were only present in grab samples where the dissolved oxygen in the overlying water was 7.5 parts per million or greater.

Thus, in summary, nymphs were (1) found only in mud or mud and fine sand substrates; (2) present on mud and fine sand to a depth of 37 feet (37.3 m) in Crystal Lake, but absent from that substrate at depths greater than 20 feet (6.1 m) in Loon Lake and 25 feet (7.6 m) in Platte Lake; (3) collected only at 70.3°F (21.3°C) in Loon Lake and 74.3°F (23.5°C) in Platte Lake, but found at 75.2 to 54.1°F (24.0 to 12.3°C) in Crystal Lake, and 64.1 to 47.5°F (17.8 to 8.6°C) in Frankfort Harbor; and (4) present only where the dissolved oxygen concentration was 7.5 parts per million or greater. Collectively, these results indicate that the absence of *Hexagenia* nymphs in grab samples collected in the thermocline and bottom waters at depths of 30 to 42 feet (9.2 to 12.8 m) in Loon Lake and at 25 to 49 feet (7.6 to 14.9 m) in Platte Lake, where the substrate was mud and fine sand, was primarily due to low concentrations of dissolved oxygen. These results together with other information describing changes in the historical composition of the fish fauna in Loon Lake (Brown and Funk 1940, Kelly and Price 1979) and excess algae production and related water quality problems in the Platte River watershed (Whelan 1999, Whitman et al. 2002, McMacken 2003) suggest that the low concentrations of dissolved oxygen in the deeper waters of Loon and Platte Lakes during summer thermal stratification are the result of cultural eutrophication in the Platte River watershed.

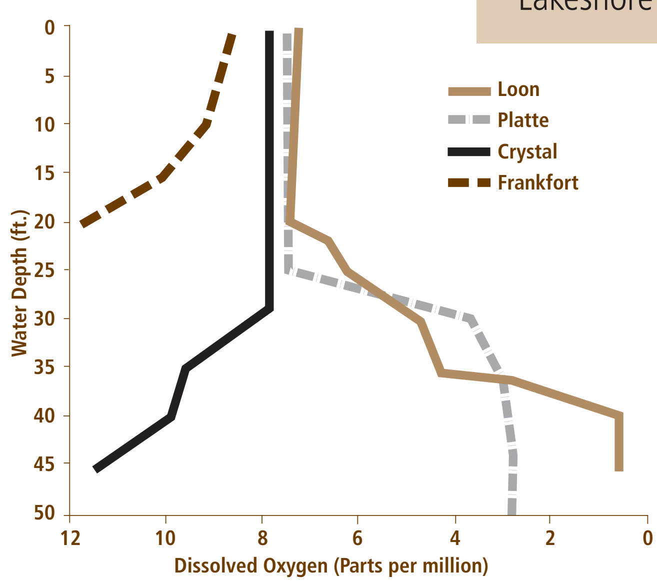

Figure 4. Dissolved oxygen concentration–water depth profiles in Loon, Platte, and Crystal Lakes and Frankfort Harbor, 24–26 July 2002.

Management recommendations

Our study was largely exploratory and not designed to pinpoint the nutrient sources that are contributing to eutrophication of the Platte River system. However, it seems clear from our study results and the other supporting information that there is a basis for concern about nutrient input to and eutrophication of Sleeping Bear Dunes National Lakeshore waters, and that the most significant nutrient sources lie outside the boundaries of the park. Thus, effectively addressing the threat to park waters posed by cultural eutrophication will need to focus not only on conditions within the park, but also in the Platte River and watershed outside the park. Additional study of the condition of the habitats and the populations of *Hexagenia* in Loon and Platte Lakes, and comparison with those in the headwater lakes in the Platte River system would more precisely identify the major sources of nutrient enrichment to the system. Additional study would also better establish a more rigorously quantitative basis for trend monitoring in the Platte River system, using burrowing mayflies as an indicator of ecosystem health. Once a formal monitoring protocol for Loon Lake is established, monitoring can readily be carried out annually by park staff to provide trend information needed to develop short- and long-term nutrient management strategies.

There is a basis for concern about nutrient input to and eutrophication of Sleeping Bear Dunes National Lakeshore waters....

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Continued in right column on page 48

folder or directory labeled with the box name, deleted the images from the camera, and moved on to the next box. At the end of each day we backed up the images on another computer.

Our productivity level was low for the first few days as we worked out the procedure and checked our work to be sure the images were of adequate quality. By the fourth day, our routine was set. In that eight-hour day we processed 600 documents or about 100 documents per hour. This included the time spent making backups, taking breaks, and handling phone calls and other business. Altogether, in a two-week period we created an inventory of 4,902 documents in the library, detailed in 7,002 images on six CDs.

Benefits of a photo inventory

The digital photos are useful for the following purposes:

1. Browsing the collection—A user can scroll through the images to see, for example, what documents are stored in the boxes labeled "Crocodilia."

2. Cataloging the collection—The images contain enough information for basic cataloging (e.g., author, title, date, subjects). This could be done at the park, or the CDs could be sent to a cataloger elsewhere. Eventually the documents will be alphabetized by the last name of the first author, but for now they remain grouped by subject and author.

3. Enhancing the catalog—When a catalog is created, the images can be included in the catalog record, allowing the searcher to view pages from any document that is retrieved by a search.

We welcome inquiries about the project.

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