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# Burrowing mayflies (*Hexagenia*) as indicators of ecosystem health

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## Abstract

Three State of the Lakes Ecosystem Conferences have been held since 1996 to encourage the development of Great Lakes indicators of ecosystem health for use in reporting on progress in restoring and maintaining the chemical, physical and biological integrity of the Great Lakes ecosystem. Here we report on the development of an indicator based on burrowing mayflies, *Hexagenia* (Ephemeroptera: Ephemeridae), using production and biomass as the indicator metrics. Burrowing mayflies were selected because they (1) were historically abundant in unpolluted, soft-bottomed mesotrophic habitats throughout the Great Lakes, (2) are intolerant of and were extirpated by pollution in most of those habitats during the 1940s to1950s, (3) have shown the ability to recover in one of those habitats following pollution abatement, (4) are ecologically important as bioturbators of lakebed sediments and as trophic integrators that link detrital energy resources directly to fishes that feed preferentially on them, and (5) have highly visible mating flights, which carry the message directly to an informed public that the source water body is healthy. In addition, their annual production can be estimated from their mean annual biomass by the size-frequency method. Productivity and biomass can also could be estimated with a 'cohort-direct' method, using the biomass of mature nymphs collected in May or early June from the cohort that is about to emerge as subimagos in late June or early July. Although both the size-frequency and cohort-direct methods provide reliable estimates of productivity and biomass, the latter method greatly reduces sample collection and processing effort and thus makes it feasible to use *Hexagenia* as an indicator of ecosystem health in surveys requiring the collection of large numbers of samples.

*Keywords*: Biomass, production, Great Lakes, SOLEC

## Introduction

The U.S. Environmental Agency and Environment Canada have hosted three State of the Lakes Ecosystem Conferences (SOLEC) since 1996 to encourage the development of Great Lakes indicators of ecosystem health. These indicators are to be used for reporting to the governments of the United States and Canada and the public on progress made in restoring and maintaining the chemical, physical, and biological integrity of the Great Lakes ecosystem, as called for in the Great Lakes Water Quality Agreement between the two countries. A description of SOLEC indicators proposed for development is available in Bertram and Statler-Salt (1998). Here we report on the development of a SOLEC indicator based on burrowing mayflies of the genus *Hexagenia* (Ephemeroptera: Ephemeridae) using production and biomass as the indicator metrics.

*Hexagenia* ranges widely in the western hemisphere,



1463-4988/01/Volume 4, pp. 283–292/$12.00 + .00 

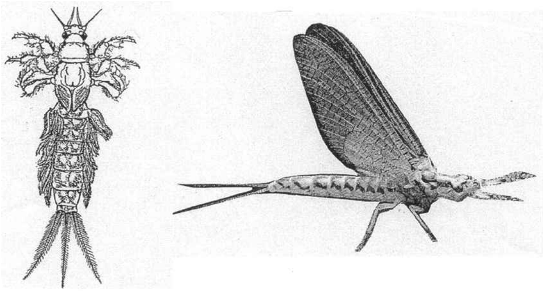

Figure 1 Burrowing mayfly (*Hexagenia*) nymph and imago (winged sub-adult).

from the Rio Negro in southern Argentina to Great Slave Lake in northwestern Canada (Edmunds et al., 1976). In North America, *Hexagenia* is most common in the eastern and central United States and adjacent areas of Canada, including the Great Lakes (Riklik and Momot, 1982; Giberson and Rosenberg, 1992; Rasmussen, 1988). In the Great Lakes, *Hexagenia* is represented by three closely related species with similar life histories: *Hexagenia limbata* (Fig. 1), *H. rigida* (Chandler, 1963; Corkum et al. 1997) and *H. bilineata* (Cochran, 1992; Cochran and Kinziger, 1997).

Great Lakes *Hexagenia* (Fig. 2) typically hatch from eggs in August and spend almost 2 years as nymphs burrowed in the lake bed. Mature nymphs emerge from their burrows in late June or early July of their third summer of life, swim to the surface of the water, and molt to become subimagos (winged sub-adults) that fly to land and rest for 1to 3 days. The subimagos molt to become adults, which mate, deposit fertilized eggs in the water, and die. A new generation (cohort) is produced annually and the population is composed of two overlapping cohorts.

The nymphs are usually most abundant in mesotrophic, soft bottomed habitats at water depths of less than 20 m (Schneider et al., 1969; Cook and Johnson, 1974; Mozley and LaDronka, 1988; Edsall et al., 1991; Schloesser et al., 1991; Dermott, 1995; Krieger et al., 1996; Edsall et al., 1999). The preferred substrate of *Hexagenia* nymphs is a mixture of clay and silt, or clay and sandy silt that is soft enough to permit burrowing and sufficiently cohesive to prevent the burrows from collapsing (Hunt, 1953; Wright and Mattice, 1981).

The nymphs are detritivores and highly active burrowers, typically penetrating the substrate to depths of 5 to10 cm (Charbonneau et al., 1997). Where abundant, they are important as bioturbators of sediment (Matisoff and Wang, 2000) and as trophic integrators that link detrital energy resources directly to fishes that feed preferentially on them (Hunt, 1953; Price, 1963; Riklik and Momot, 1982; Hayward and Margraf, 1987; Schaeffer, 1994; Synnestvedt, 1996; Beamish et al., 1998).

The *Hexagenia* mating swarm is highly visible and can carry the message to an informed public that the water body inhabited by the nymphal population is healthy. Mating swarms have recently been documented

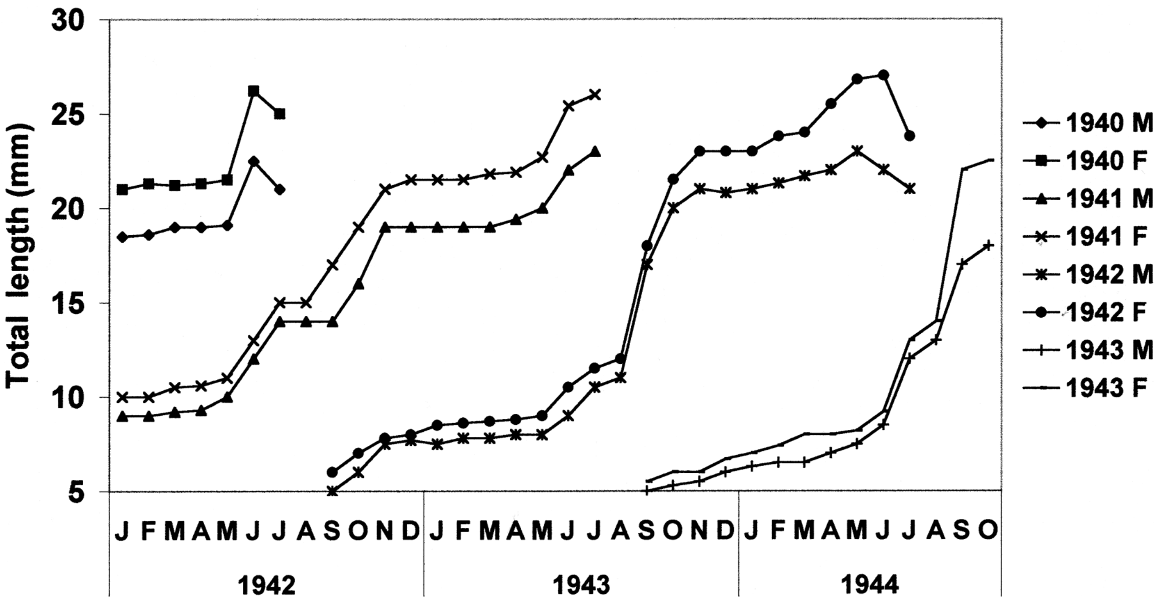


Figure 2 Growth in length (mm) of *Hexagenia* nymphs. Nymphs are about 0.8 mm long at hatching in August. After Chandler (1963).

at a number of sites in Lake Erie, and one swarm 6 km wide and 24 km long was recently recorded on weather station Doppler radar (Masteller and Obert, 2000).

*Hexagenia* was historically abundant in the Great Lakes until the 1940s to1950s when major population declines occurred in all of their major, traditional habitats (Schneider et al., 1969; Cook and Johnson, 1974; Mozley and LaDronka, 1988; Edsall et al., 1991, 1999; Schloesser et al., 1991). These declines were linked to eutrophication and low dissolved oxygen in bottom waters (Britt, 1955; Beeton, 1961, 1969; Verduin, 1964; Carr and Hiltunen, 1965; Krieger et al., 1996), and pollution of sediments by metals and petroleum products (Edsall et al., 1991; Schloesser et al., 1991).

Improvements in water and sediment quality in their historical habitat, which began in the 1960s, were not immediately followed by the recovery of these populations, but there is recent evidence of the beginnings of recovery in lower Green Bay, Lake Michigan (Cochran, 1992; Cochran and Kinziger, 1997) and in Saginaw Bay, Lake Huron, where a localized mating swarm was reported in 1999, and recovery may be nearly complete in western Lake Erie (Madenjian et al., 1998; Edsall et al. (1999).

Thus, *Hexagenia* has a number of characteristics, including its historical abundance in mesotrophic habitats, intolerance to pollution, ability to recover following pollution abatement, ecological importance as a sediment bioturbator and trophic integrator, and highly visible mating swarms, that make it attractive to consider as an indicator of ecosystem health in the Great Lakes. In addition, the literature and other available information show that an indicator based on *Hexagenia* has the potential to satisfy the SOLEC requirements that the indicator be scientifically based, quantitative, a reasonably objective representation of environmental condition, and easily understood by non-technical audiences.

## Indicator development

There is a substantial literature on *Hexagenia* in the Great Lakes that provides a useful context and background for indicator development (see Edsall et al., 1999 for a recent review). Most of this information is for Lake Erie, and describes the changes in abundance in the nymphal life stage based on sampling of living populations from the 1930s to the late 1990s. A continuous record of *Hexagenia* abundance, from about 1740 to1990, is also available from sediment cores taken in Lake Erie in 1988 to 1991, which contained the fossilized mouth parts of *Hexagenia* (Fig. 3). Where they overlap, trends in the sediment-fossil record are in general agreement with those from living populations. Records of abundance based on samples from living populations in portions of Lakes Huron, Michigan, and their connecting channels and from Lake Ontario, and on observations of mating swarms are also available. Fish diet studies also provide information from living populations on the general abundance of *Hexagenia*.

Despite the large amount of information on numerical abundance (usually expressed as density, D, the number of nymphs per $m^2$ of lake bed), indicator development was not based on that metric because the nymphs range in size from about 0.8 mm total length at hatching to about 30 mm at emergence as subimagos. Thus, D does not provide a useful estimate of the size of the trophic resource unless the size composition of nymphs is also provided. To avoid this problem, annual production (P) was selected as the primary metric for indicator development, and mean annual biomass (B) as a supporting metric. Production was selected because it integrates recruitment, growth, and mortality to provide a measure of the trophic resource, and when considered together with B provides a measure of turnover (P/B), which can be substantial in *Hexagenia* populations and therefore important from an ecological perspective (Waters, 1977; Benke, 1984).

## Estimating biomass and production

Typically, P is estimated from B data, which are collected by sampling the *Hexagenia* population monthly during the ice-free portion of one 12-month period. For example, one set of P and B data on which this paper is based was obtained from a recent study of *Hexagenia* in Lake St. Clair (Edsall et al., in press), which was performed as follows. Lakebed sediment and nymphs burrowed in the sediment were collected with a Ponar grab. Each grab sample was washed on a fine-mesh (0.65 mm) screen and the nymphs and extraneous particulate material remaining on the screen were placed in formalin and taken to the laboratory. In the laboratory, each sample was examined under 7x magnification and the nymphs were extracted manually and measured (total length to the nearest 0.5 mm). Preserved lengths were converted to dry weight using equations from the literature (Edsall et al., 1991). Production and its variance were estimated with the size-frequency method of Hynes as modified by Hamilton (1969), and with equations from

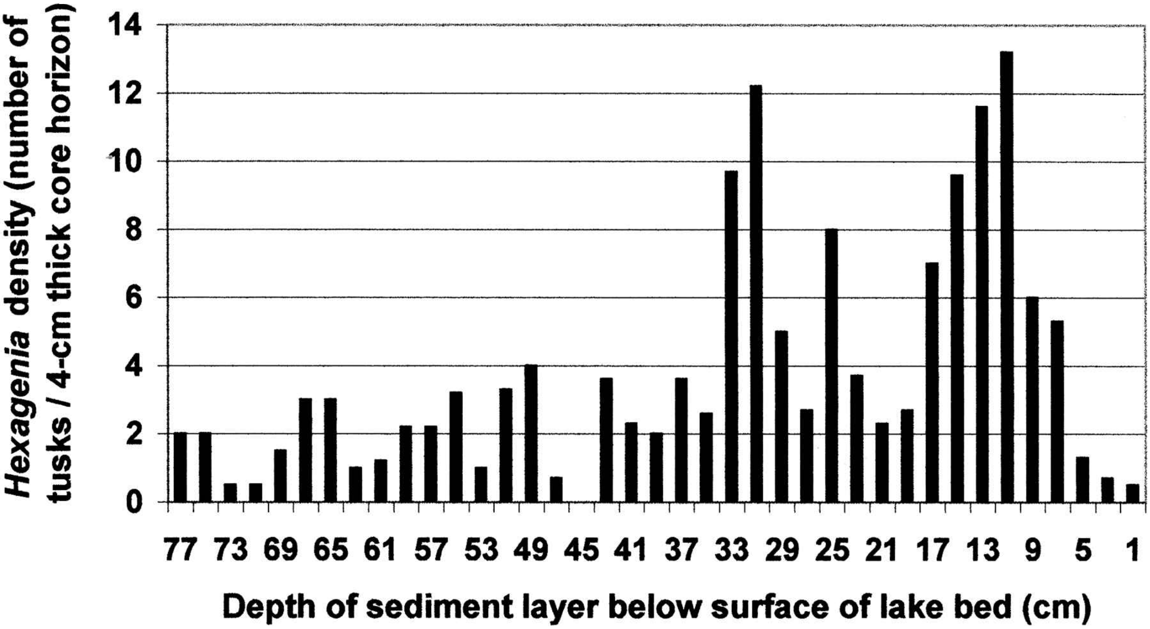


Figure 3 Trends in abundance of burrowing mayflies (*Hexagenia*) in western Lake Erie, as shown by the number of fossilized nymph tusks (heavily sclerotized mouth parts) in sediment core layers. Nutrient influx caused by the draining of the Black Swamp in northern Ohio in the late 1880s is reflected by an increase in the abundance of *Hexagenia* in layers 33-31. The increase in abundance in layers 17-11 reflects increased nutrient input as cultural eutrophication in the 1930s-1940s. Pollution exceeded critical levels, eutrophication depleted oxygen in the bottom water and the population declined sharply in the late 1950s. After Reynoldson and Hamilton (1993).

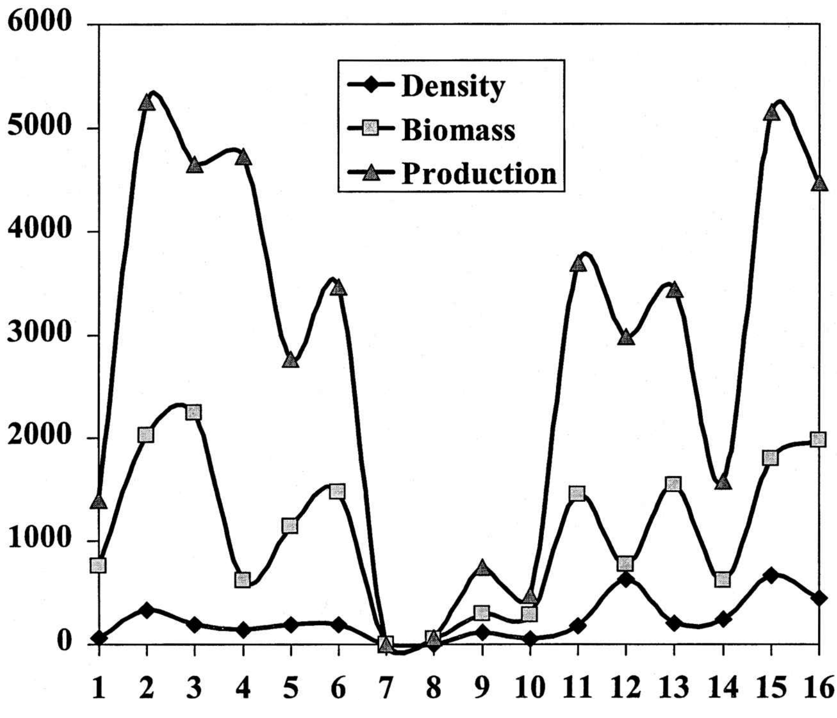


Figure 4 Mean annual density (number $m^{-2}$ $yr^{-1}$)and biomass and annual production (mg dry weight $m^{-2}$ $yr^{-1}$) of *Hexagenia* nymphs collected at 16 stations in Lake St. Clair, 1995-1996. After Edsall et al. (in press).

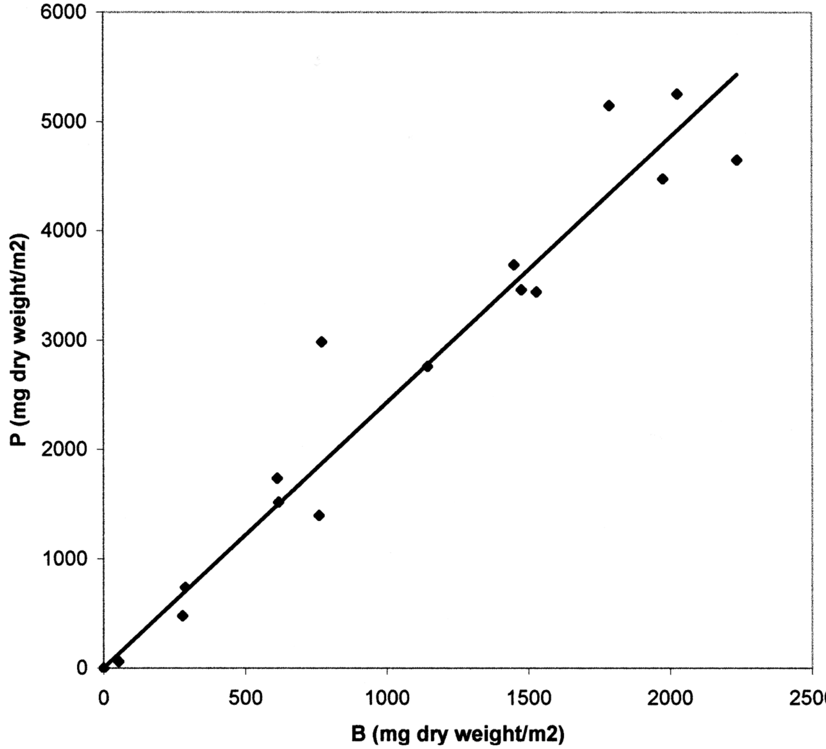


Figure 5 Annual production (P) and mean annual biomass (B) relation for *Hexagenia* nymphs in Lake St. Clair, 1995-1996 (P = 2.4 B; $R^2$ = 0.94; n = 16). P and B units are mg dry weight $m^{-2}$ $yr^{-1}$. After Edsall et al. (in press).

Krueger and Martin (1980) and a cohort production interval (Benke, 1979) consistent with a 2-year life cycle. The size-frequency method is widely accepted for estimating P in *Hexagenia* populations because it permits direct comparison of results with most other production studies of *Hexagenia*; does not require the identification of cohorts to produce reliable results; and can be applied to samples containing nymphs of more than one *Hexagenia* species, if those species have the same life span and reach the same maximum size.

The estimates of D, B and P shown in Fig. 4 are from Edsall et al. (in press). The absence of nymphs at station 7 and the very low D at station 8 were attributed to pollution. These stations bracket the mouth of a major tributary to the lake, which is heavily polluted by metals, oil and grease, and by periodic sewerage system overflows to the river. The relatively low D, B, and P values at stations 9 and 10, which are outside the immediate influence of the polluted tributary, were attributed to unfavorably coarse sediment grain-size distribution at those locations.

From the data of Fig. 4, a linear regression of P against B and passing through the origin (Fig. 5) yielded the equation

$$P = 2.4B \quad (R^2 = 0.94; n = 16) \qquad (1)$$

This equation provides a simple way of estimating P when B is known. When stated as a ratio of P to B, it yields the measure of turnover in the population

$$P/B = 2.4 \qquad (2)$$

The addition of the other published B and P data from the northern United States and Canada (39° to 53° North latitude) to Fig. 5 improved the fit of the regression, changed it slightly to

$$P = 2.5B \quad (R^2 = 0.96; n = 35) \qquad (3)$$

(Fig. 6), and showed that the relation was broadly stable across a number of rivers and lakes in North America. A P/B value of 2.5 is similar to those reported for *Hexagenia* by others (e.g., Riklik and Momot, 1982; Flannigan and Cobb, 1984; Heise et al., 1988) and is also consistent with the expected value for an aquatic insect with a 2-year life cycle and overlapping cohorts, as rea-

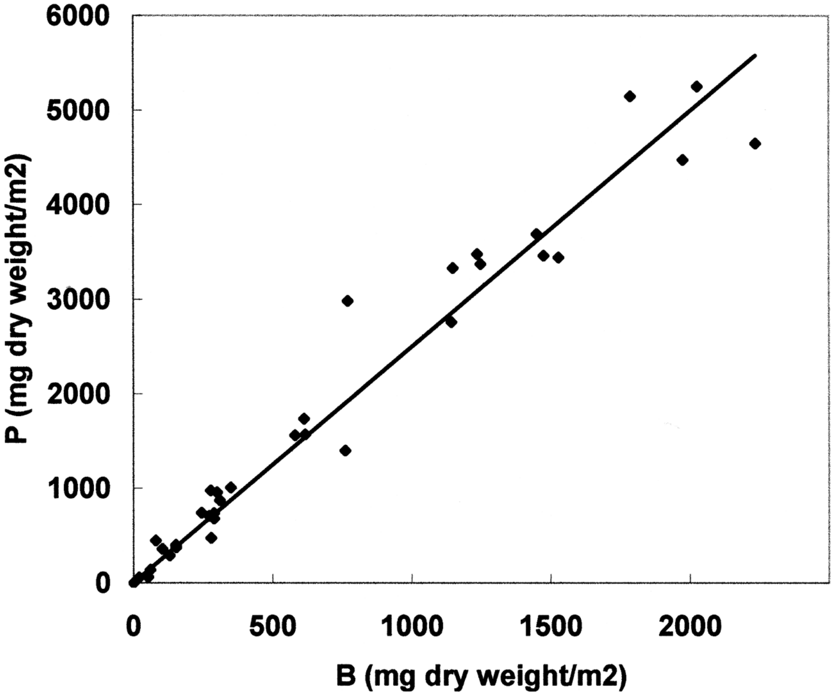


Figure 6 Annual production (P) and mean annual biomass (B) relation for *Hexagenia* nymphs at 39-53° North Latitude in North America (P = 2.5 B; $R^2$ = 0.96; n = 35). P and B units are mg dry weight $m^{-2}$ $yr^{-1}$. After Edsall et al. (in press).

soned by Waters (1977) and Benke (1984). Thus, equation 3 should be of use in estimating the production of *Hexagenia* in the northern United States and Canada.

Although this approach provides reliable estimates of B and P, the process is labor intensive. Sampling is required monthly for 6 to 7 consecutive months and the fine-mesh screen that is needed to collect the smallest nymphs also collects the coarser sediment particles and detritus, which impede locating and extracting the smaller nymphs. These problems generally preclude the routine use of the size-frequency method for large-scale monitoring and assessment of *Hexagenia* using P and B as metrics.

## A cohort-direct method for estimating biomass and production

The observation that mean monthly biomass in Lake St. Clair was highest among nymphs longer than about 16 mm and that it peaked in June in the cohort that was about to emerge as imagos in early July (Fig. 7; Edsall et al., in press) suggested an alternative method for estimating B and P. This alternative cohort-direct method relies on the direct measurement of the biomass of a sample of nymphs collected in June from the cohort that is about to emerge as imagos. Regression analysis performed on the data from Lake St. Clair (Edsall et al., in press) and from the upper Great Lakes connecting channels (Edsall et al., 1991; T.A. Edsall, unpublished data) showed that the biomass of these large, mature nymphs in June (BE) provided reliable estimates of B (B = 280 + 0.47 BE; $R^2$ = 0.79; Fig. 8) and P (P = 509 + 2.14 BE; $R^2$ = 0.79; Fig. 9). Thus, BE can be used as an estimator of population B or P, or independently as an index of the status of the emerging cohort or of the *Hexagenia* population.

Significant advantages of the cohort-direct method are that sampling need only be conducted once annually at each location in June, before emergence, and that a coarse screen can be used in the field to expedite washing the Ponar grabs and collecting the larger nymphs. To test this approach we collected 25 sediment samples with a Ponar grab at one location in Lake St. Clair in June 2000 and washed them individually on a coarse-mesh (3.2 mm) screen. Sediment and plant detritus passed quickly through the screen while the large nymphs of the 1998 cohort that were about to emerge as imagos were retained on the screen and were easily extracted manually for preservation in formalin. The screen also retained *Chara*, which is common in the

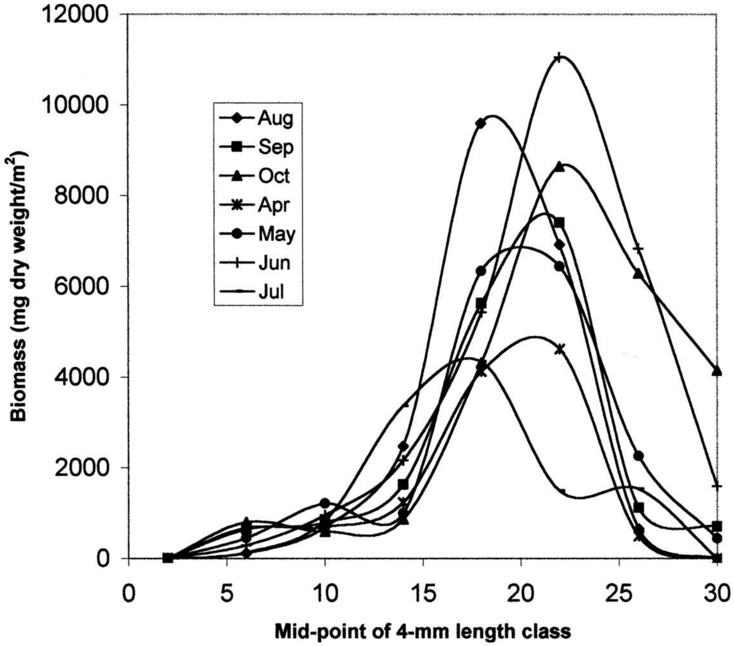


Figure 7 Mean monthly biomass (mg dry weight m$^{-2}$) of *Hexagenia* nymphs by 4-mm size classes in Lake St. Clair, 1995-1996. T.A. Edsall, unpublished data.

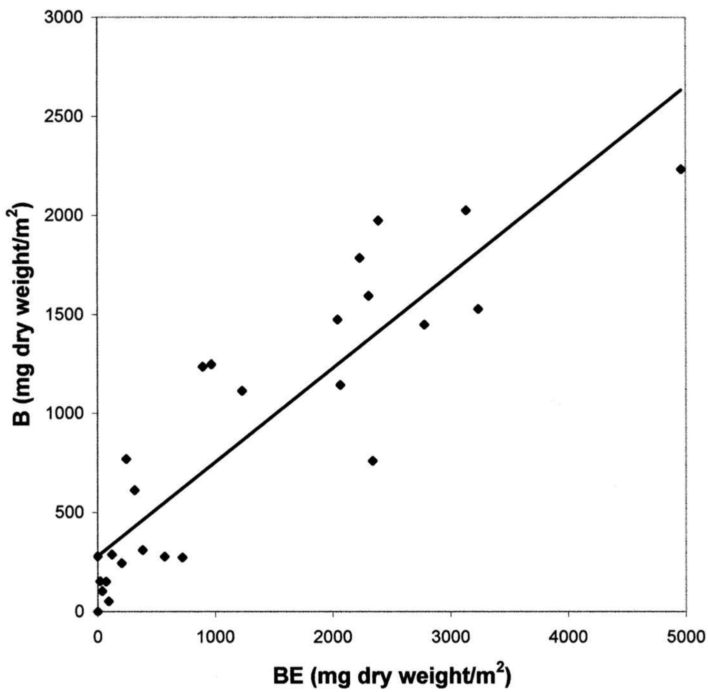


Figure 8 Relation between mean annual biomass (B; mg dry weight m$^{-2}$ yr$^{-1}$) and the biomass of the emerging cohort (BE; mg dry weight m$^{-2}$) in June, just prior to emergence. Data from the upper Great Lakes connecting channels, 1986, and Lake St. Clair, 1995-1996. After Edsall et al. (in press); Edsall et al. (1991); T. A. Edsall, unpublished data.

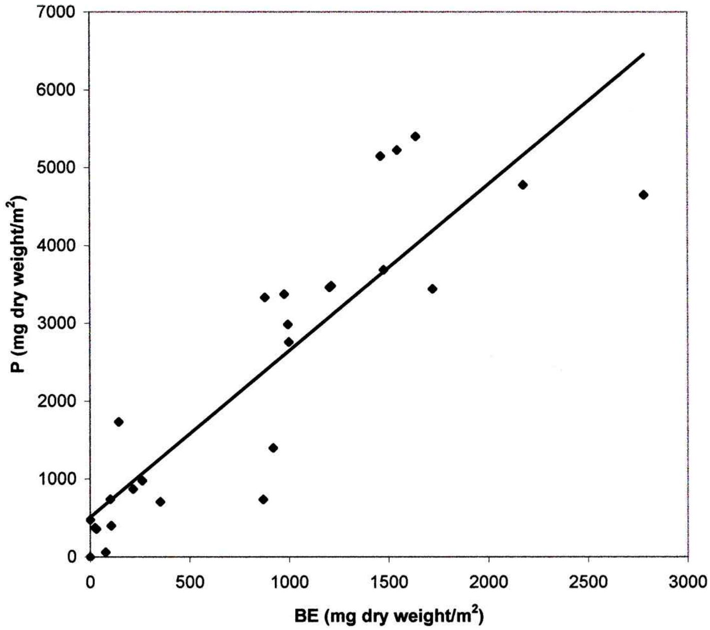


Figure 9 Relation between annual production (P; mg dry weight $m^{-2}$ $yr^{-1}$) and the biomass of the emerging cohort (BE; mg dry weight $m^{-2}$) in June, just prior to emergence. After Edsall et al., (in press); T. A. Edsall, unpublished data.

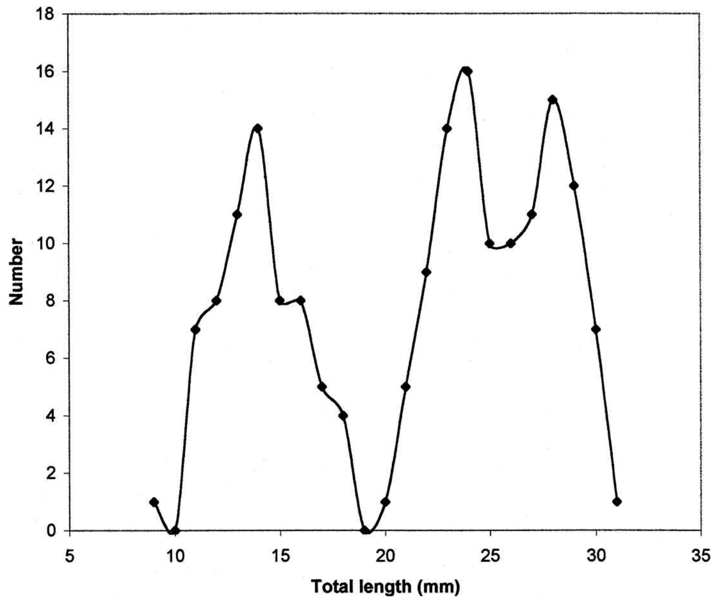


Figure 10 Length-frequency distribution of *Hexagenia* nymphs in Ponar grab samples collected in June 2000 in Lake St. Clair and washed on a 3.2-mm screen. The 1999 cohort is represented by nymphs less than 20 mm long and the 1998 cohort, which is about to emerge as subimagos, is represented by nymphs 20 mm and longer. The modal length of the1998 cohort was about 24 mm for males and about 28 mm for females. T.A. Edsall, unpublished data.

Lake, and some nymphs of the 1999 cohort. The 1998 cohort was easily distinguished from the 1999 cohort (Fig. 10), suggesting the emerging cohort could be reliably extracted from samples in the field without having to measure individual nymphs. Sample processing in the laboratory would then only require obtaining a single dry weight for the sample.

The time saved in sample collection in the field and sample processing in the laboratory with the cohort-direct method could be substantial. Samples would be collected only once, in June, instead of monthly, April to October, and the time required to extract the nymphs from each Ponar sample in the field would be reduced from about 10 min to <5 min. The extraction time for a sample in the laboratory is about 5 min and another 5 min would be required to obtain a dry weight measurement. In contrast, extraction of the nymphs in the laboratory from a sample collected with the fine-mesh screen can take up to 2 d, and an additional hour may be needed to measure the nymphs. Data entry for the size-frequency method requires entering one value (length measurement) for each nymph in the sample, whereas the cohort-direct method requires entering only one value (dry weight measurement) per sample.

## Summary and conclusion

This paper describes development of a SOLEC indicator of ecosystem health based on estimates of B and P obtained by sampling populations of *Hexagenia* nymphs. Although the size-frequency method provides reliable estimates of B and P for North American populations, the sample collection and processing can be extremely labor intensive. An alternative cohort-direct approach described here is much less labor intensive and provides an estimate of cohort biomass (BE) which can be reliably translated into estimates of B and P for the population. The cohort-direct approach requires (1) sampling in June to collect the large, mature nymphs in the cohort that is about to emerge as subimagos; (2) washing Ponar grab samples on a large-mesh (3.2 mm) screen in the field, which rapidly separates the large *Hexagenia* nymphs in the grab sample from the sediment, plant material, and detritus in the sample; and (3) in the laboratory, directly measuring the combined dry weight of the nymphs in the emerging cohort in each sample. The biomass of that emerging cohort (BE) can be reliably translated into estimates of B and P for the population, or it can be used as an independent estimate of the status of the emerging cohort or of the population. This cohort-direct method makes it feasible to use *Hexagenia* as an indicator of ecosystem health in the Great Lakes and perhaps also in other areas of North America.

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