Chapter 20

Trophic Relationships of Macroinvertebrates

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20.1 INTRODUCTION

A major observation resulting from studies of aquatic invertebrate feeding (e.g., Berrie, 1976; Cummins and Klug, 1979; Anderson and Cargill, 1987; Palmer et al., 1993a; Wotton, 1994; Berg, 1995) is that, based on food ingested, essentially all aquatic invertebrates are omnivorous. For example, aquatic insects that chew leaf litter in streams, termed *shredder detritivores*, ingest not only the leaf tissue and associated microbiota, (e.g., fungi, bacteria, protozoans, microarthropods), but also diatoms (e.g., Plague and Wallace, 1998) and other algae that may be attached to the leaf surface, as well as very small macroinvertebrates (e.g., first-instar midge larvae). For this reason, the trophic level analysis pioneered by Lindeman (1942), and used extensively in investigations of trophic relationships in marine, freshwater, and terrestrial communities, does not lend itself well to simple trophic categorization of stream macroinvertebrates (e.g., Coffman et al., 1971).

An alternate classification technique involves the functional analysis of stream macroinvertebrate feeding based on morphobehavioral adaptations for food acquisition (Table 20.1). This functional feeding group (FFG) approach, described over 40 years ago (Cummins, 1973), has been modified in some detail since then (e.g., Cummins, 1974; Cummins and Klug, 1979; Wallace and Merritt, 1980; Merritt et al., 1984, 1996, 1999, 2002, 2008; Cummins and Wilzbach, 1985; Mattson et al., 2014), but the basis of FFG relationships remains quite simple. FFGs are based on a direct correspondence between the categories of nutritional resources present in the freshwater environment and the populations of macroinvertebrates that are adapted to efficiently harvest a given food resource. As the relative availability of basic food resources changes through space or time, there is a concomitant change in relative abundances of the functional groups of freshwater macroinvertebrates. Thus a limited set of feeding adaptations found in freshwater invertebrates is linked with their basic food resource categories.

As the great stream ecologist Noel Hynes observed (Cummins, personal communication), stream insects worldwide exhibit similar morphological and behavioral adaptations even though they differ taxonomically. Thus two mayfly taxa in different families may be in the same FFG (Fig. 20.1). A further example is the similarity in scraper mandibles—used to dislodge attached periphyton from surfaces of different taxa (Fig. 20.2). These similarities in adaptations for acquiring food are the basis of the FFG approach in which taxonomy of stream macroinvertebrates is applied only to the level of resolution necessary to assign them to one of the five major FFGs: shredder-detritivores, shredder-herbivores, filtering-collectors, gathering-collectors, scrapers, piercer-herbivores, and predators (Table 20.1, Fig. 20.3).

The basic food resources for macroinvertebrates in stream ecosystems can be categorized as (1) coarse particulate organic matter (*CPOM*) (particles greater than 1 mm in size) including riparian-derived litter consisting of leaves, needles, bark, twigs, and other terrestrial plant parts, large woody debris (LWD) (i.e., large branches and logs) (see Chapter 26); (2) live macrophytes including macroalgae and rooted and floating vascular plants (see Chapter 13); (3) fine particulate organic matter (*FPOM*) (particles ranging from 0.5 μm to 1.0 mm in size) generally composed of unattached living or detrital material including flocculated dissolved organic matter (DOM), DOM with Ca and Mg, and particles created through physical and biological reduction of CPOM and associated microbiota (see Chapter 25); (4) *periphyton*, predominantly

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TABLE 20.1 General classification system for aquatic macroinvertebrate Functional Feeding Groups (FFG).

Functional Group (General Category Based on Feeding Acquisition Adaptations)	Subdivision of Functional Groups		Examples of Taxa	General Particle Size Range of Food (in mm)
	Dominant Food	Feeding Mechanism		
Shredder detritivores	Living vascular hydrophyte plant tissue	Herbivores—chewers and miners of live macrophytes	Trichoptera: Phryganeidae, Leptoceridae	>1
Shredder herbivores	Decomposing vascular plant tissue and wood—coarse particulate organic matter	Detritivores—chewers, wood borers, and gougers	Plecoptera: Nemouridae, Peltoperlidae Diptera: Tipulidae, Trichoptera: Limnephilidae, Lepidostomatidae Crustacea: Amphipoda	
Collectors	Decomposing fine particulate organic matter			
Filtering collectors		Detritivores—filterers or suspension feeders	Trichoptera: Hydropsychidae, Diptera: Simuliidae	<1
Gathering collectors		Detritivores—gatherers or deposit (sediment) feeders (includes surface film feeders)	Ephemeroptera: Ephemeridae Diptera: Chironomidae	
Scrapers	Periphyton—attached algae and associated material	Herbivores—grazing scrapers of mineral and organic surfaces	Trichoptera: Glossosomatidae Coleoptera: Psephenidae Ephemeroptera: Heptageniidae	<1
Piercer-herbivores		Herbivores—suck contents of algal cells	Trichoptera: Hydroptilidae	<1
Predators	Living animal tissue	Carnivores—attack prey, pierce tissues and cells, and suck fluids	Hemiptera: Belostomatidae Naucoridae	>1
	Living animal tissue	Carnivores—ingest whole animals (or parts)	Odonata, Plecoptera: Perlidae Megaloptera: Corydalidae Sialidae	>1

Modified from Merritt et al. (2008).

attached algae (especially diatoms) and associated material growing on rock, wood, and plant surfaces (see Chapters 11 and 12); and (5) *prey*, all invertebrates captured by predators, predominantly small species and early instars of large species (see Chapters 14, 15, and 18).

These five nutritional resource categories are related to macroinvertebrate feeding adaptations and were chosen on the basis of the size range of the material (coarse or fine) and the general location of the food, such as attached to surfaces (periphyton), suspended in the water column (seston), deposited on the sediments, found in litter accumulations, or dispersed in the form of live invertebrate prey. This categorization also reflects (1) biochemical differences in nutritional resources, such as the presence of living chlorophyll in periphyton or microorganisms on CPOM, and (2) the major source of the food, such as whether it was either *autochthonous* (produced within the aquatic system; see Chapters 11, 13, and 34) or *allochthonous* (produced from the streamside riparian area; see Chapter 28).

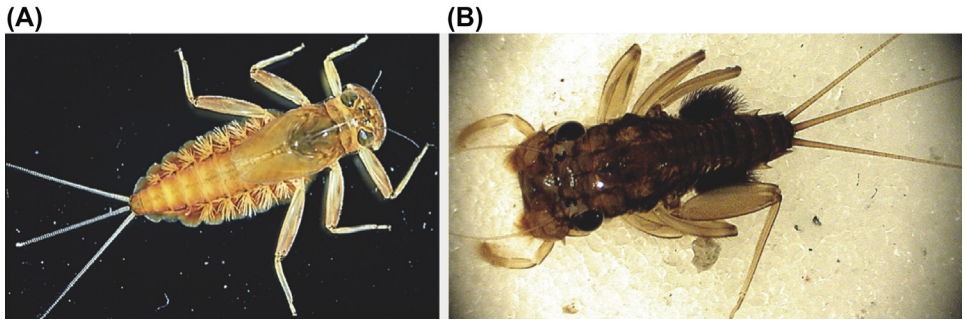

FIGURE 20.1 Two mayflies in the same functional feeding group (scraper) but in different families and from different regions. (A) Heptageniidae from North America, (B) Leptophlebiidae from Brazil. *After Hamada et al. (2014).*

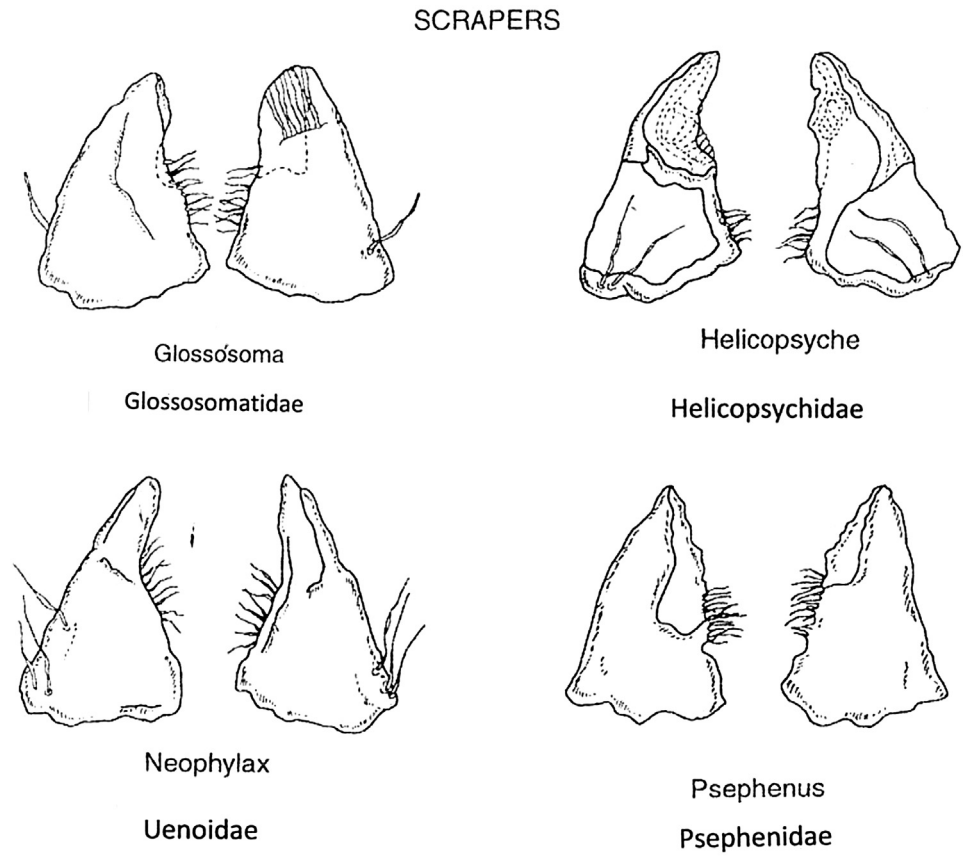

FIGURE 20.2 Similarity of mandible structure of four different scraper taxa representing three Trichoptera families (Glossosomatidae, Helicopsychidae, Uenoidae) and a Coleoptera family (Psephenidae). All the mandibles have a flat sharp edge that scrapes attached periphyton free and a concave inner surface with associated setal brushes that aid in moving the removed food into the mouth. *Modified from Merritt et al. (2008).*

The general FFG classification system of stream macroinvertebrates, in which taxa are categorized according to the different morphological–behavioral adaptations used to acquire nutritional resources, is presented in Table 20.1. Some representative FFG taxa are listed in Table 20.1 and shown in Fig. 20.3. These feeding adaptations determine which of the categories represent the primary food resource: (1) *shredders* feed on CPOM, (2) *collectors* feed on FPOM, (3) *scrapers* consume periphyton, (4) *piercers* feed on live algal cell contents in periphyton, and (5) *predators* ingest prey. The functional groups described in this classification are analogous to *guilds*, defined as groups of organisms using a particular resource class (Root, 1973; Georgian and Wallace, 1983; Hawkins and MacMahon, 1989); thus function in FFGs is defined as use of similar resource classes.

Within each FFG, there are obligate and facultative members. These can be different species or different stages in the life cycle of a given species. For example, it is likely that most aquatic insects, including predators, are facultative gathering-collectors as early instars (Petersen, 1974). Thus the most reliable linkage between a food resource category (CPOM, FPOM, periphyton, prey) and macroinvertebrates is with the obligate forms in later instars. The distinction between obligate and facultative status is best described by the efficiency with which a given invertebrate converts a food

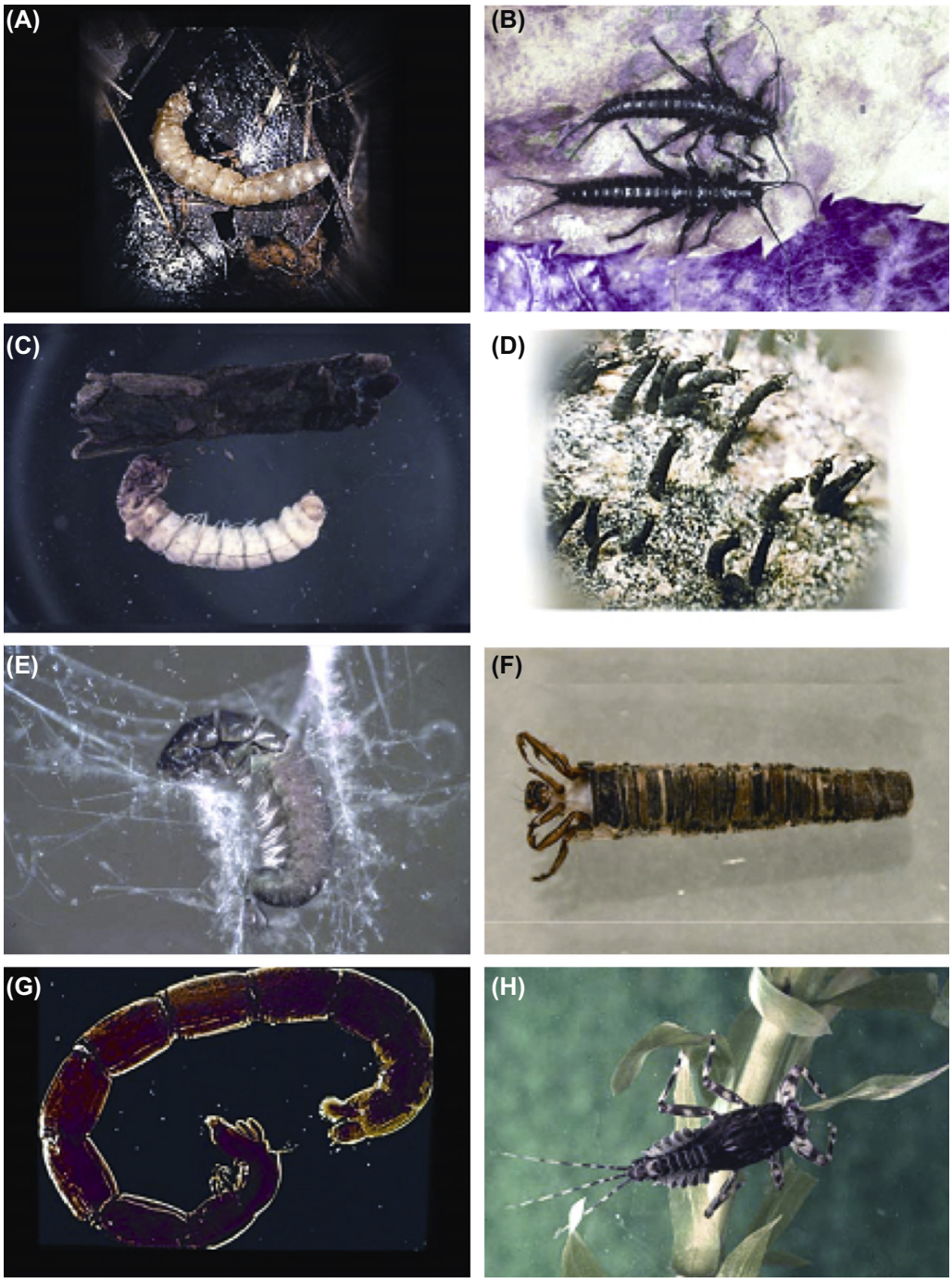

FIGURE 20.3 Representative functional feeding group stream taxa. **Shredders** (A. Diptera: Tipulidae, B. Plecoptera: Pteronarcyidae, C. Trichoptera: Limnephilidae); **Filtering Collectors** (D. Diptera: Simuliidae, E. Trichoptera: Hydropsychidae, F. Trichoptera: Brachycentridae); **Gathering Collectors** (G. Diptera: Chironomidae, H. Ephemeroptera: Ephemerellidae, I. Ephemeroptera: Ephemeridae); **Scrapers** (J. Ephemeroptera: Heptageniidae, K. Trichoptera: Glossosomatidae, L. Coleoptera: Psephenidae); **Piercers-Herbivores** (M. Trichoptera: Hydroptilidae); and **Predators** (N. Plecoptera: Perlidae, O. Megaloptera: Corydalidae, P. Odonata: Gomphidae).

resource into growth (Cummins and Klug, 1979). It is important to understand that the same morphobehavioral adaptation can result in the ingestion of a wide range of food items, the intake of which constitutes trophic classification: herbivory (i.e., living plants; Gregory, 1983; Lamberti and Moore, 1984; Webster and Benfield, 1986); detritivory (i.e., dead organic matter; Anderson and Sedell, 1979; Wallace and Merritt, 1980; Short, 1983; Webster and Benfield, 1986; Cummins et al., 1989; Palmer et al., 1993b); or carnivory (i.e., live animal prey; Allan, 1983; Peckarsky, 1984).

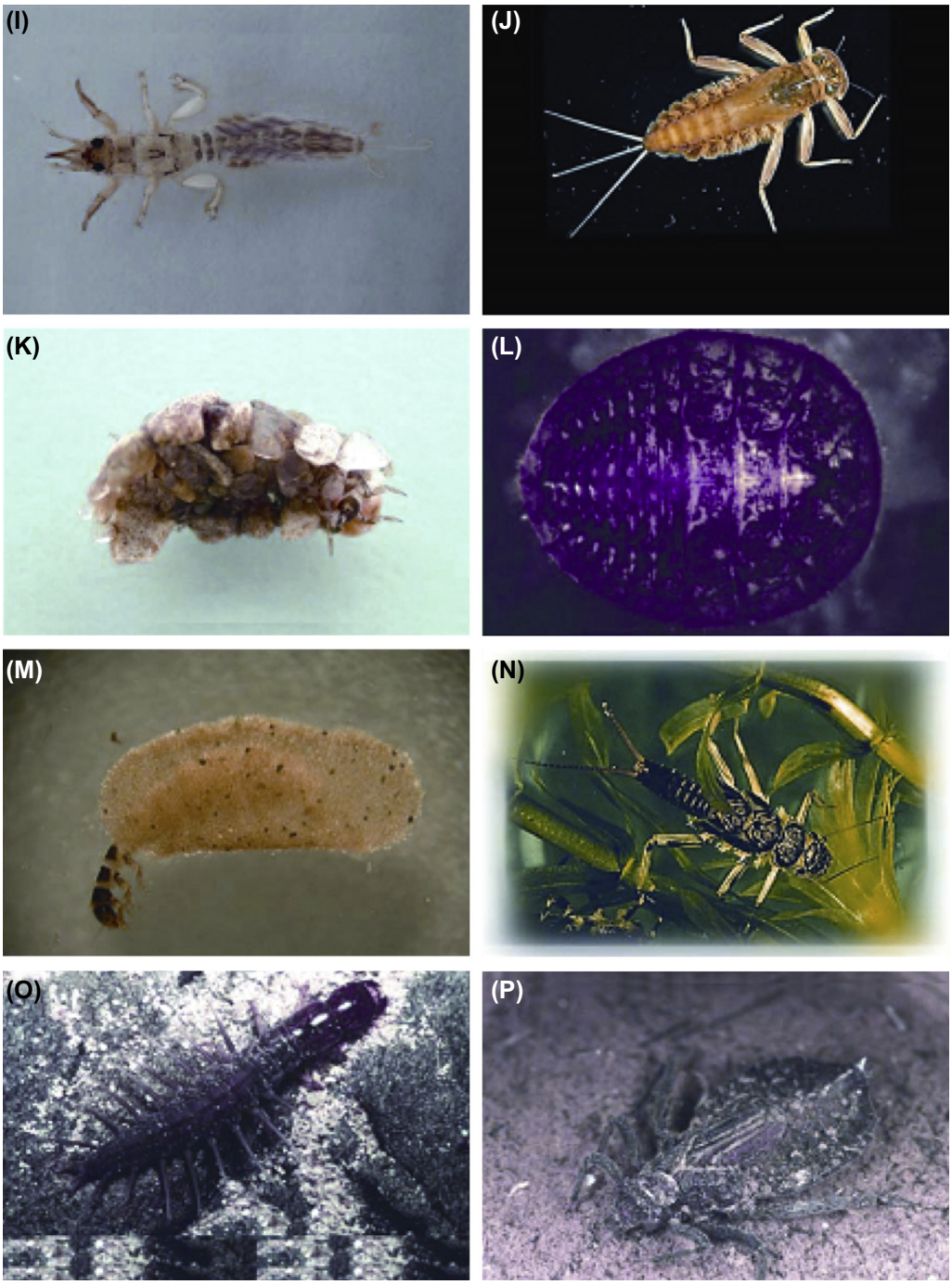

FIGURE 20.3 cont'd

Although intake of different food types can be expected to change from season to season, from habitat to habitat, and with growth stage, limitations in stream macroinvertebrate adaptations for food acquisition have been shaped over evolutionary time, and these are relatively fixed. For example, a scraper such as the mayfly *Stenonema* (Heptageniidae), whose mouthparts are adapted for shearing off algae attached to surfaces, may ingest a variety of material in the periphyton dictated by its food-harvesting morphology without any change in behavior. As stream macroinvertebrates get larger, microhabitats scraped for food may change or items scraped from surfaces may differ (Cummins, 1980). Comparable (homologous) morphological structures that enable insects to scrape periphyton from substrates can be found in the very similar mandibles of taxonomically diverse groups such as the trichopteran families Glossosomatidae (saddle-case makers)

and Helicopsychidae (snail-case makers), and the coleopteran family Psephenidae (water penny beetles). Such similarity of structure is a striking example of convergent evolution and the basis of the FFG categorization.

The FFG approach is informative in that it allows an assessment, numerically or by biomass, of the degree to which the macroinvertebrate biota of a given stream is dependent upon a particular food (nutritional) resource. It also makes apparent the linkages that exist between food resources and macroinvertebrate morphological−behavioral adaptations (e.g., Cummins, 1974; Grubbs and Cummins, 1996). As the relative dominance of various food resource categories changes, a corresponding shift in the ratios of the different FFGs is to be expected. Therefore invertebrate FFG analysis is sensitive to both the normal pattern of geomorphic and concomitant biological changes that occur along river systems from headwaters to lower reaches (e.g., Vannote et al., 1980), partitioning between habitats (e.g., Mattson et al., 2014), as well as to alterations in these patterns resulting from human impact (Cummins, 1992, 1993). The objective of this chapter is to demonstrate how the relative abundance (ratios) of FFGs can be used as surrogates for these aquatic ecosystem attributes and serve as a useful assessment of the ecological condition ("health") of freshwater communities. To accomplish this goal, we describe how invertebrates are organized into FFG categories and develop a set of ratios that can serve as surrogates for ecosystem attributes (Table 20.2). These ratios can be compared to proposed threshold values for appropriate ecosystem attributes to produce a qualitative evaluation of stream ecosystem condition.

20.2 GENERAL DESIGN

The general procedure described below focuses on identifying key functions in stream macroinvertebrate communities that can be determined at varying levels of taxonomic resolution. The technique is particularly useful for macroinvertebrate groups for which the state of taxonomic knowledge is poorly known. For example, determination of community structure for many groups of macroinvertebrates is based on measures of *taxa* richness or diversity (i.e., some combination of ordinal, family, and generic identifications), not on species richness or diversity. (Note that "species diversity" is inaccurate because diversity calculations are almost never based on species-level taxonomy.) FFG analysis enables the evaluation of macroinvertebrate communities at a range of levels of taxonomic resolution. This approach maximizes the ecological information obtained for the taxonomic effort expended. For example, determination of FFGs in the Odonata (dragonflies and damselflies) is achieved by separation to order alone. In contrast, FFG assignment for some subfamilies of Chironomidae (midges) or genera of mayflies in the family Ephemerellidae may require species-level identifications.

20.2.1 Site, Habitat, and Timing of Sampling

Sites should be selected to ensure that the basic habitats are included: (1) coarse sediments of riffles (golf ball−sized to bowling ball−sized cobbles), (2) accumulations of organic litter and small woody debris (handful amounts), (3) fine sediments in depositional zones (the upper 1−2 cm from an area at least 0.5 m^2), (4) rooted vascular macrophytes, and (5) LWD. Because the results are presented as dimensionless ratios, they are relatively independent of sample size.

If some habitat types are not present, the compromise might be, for example, that any erosional habitat present may have to suffice or be replaced by LWD as the only stable habitat where scrapers and filtering collectors can acquire appropriate attachment sites or food. In many streams, rooted vascular plants are not present and LWD may be scarce or absent. The three habitats that normally capture the full range of FFGs are coarse and fine sediments and plant litter of riparian origin. If samples are treated separately, results can be weighted for percent cover of each of the habitat types, which naturally favor different functional groups (e.g., cobble-scrapers and filtering-collectors; leaf litter-shredders; fine sediments−gathering-collectors). This can be helpful in providing a more balanced view of the study reach, but often FFG ratios by habitat vary little from analysis of composite samples (e.g., Cummins et al., 2005). However, it is very important to point out that the many protocols that limit sampling to riffles will not provide information on shredders, and therefore yield little or no insight into the linkage of the stream community with the riparian zone (e.g., Cummins et al., 1989; Cummins, 2002).

20.2.2 Collection and Processing of Samples

All sampling can be accomplished using a D-frame net (see Chapter 15) or a robust aquarium net. Quantitative samples can also be taken with a Surber or Hess-type sampler (Chapter 15). Provided that the seasonal sampling issue is addressed (see later section), a net mesh size of 0.5 mm is usually adequate, but 0.25 mm is even better because of the capture of more first instars and some small Chironomidae. The net is held downstream and below a cobble or leaf pack as it is lifted from the stream, or the net is used to scoop surface sediments (~2 cm depth) from depositional habitats, or scraped over the surface

of LWD. If rooted vascular plants represent a significant habitat, they are shaken vigorously in front of the net (Merritt et al., 2008). Sample processing is rapid and can be conducted streamside. The significant advantages of sorting live samples in the field are that live animals are more easily detected and retain their colors and behaviors, which are often absent in preserved samples. After sorting and enumeration by FFGs, samples can always be preserved and returned to the laboratory for more detailed taxonomic determinations.

Processing streamside can be accomplished by washing the sample from the net into a white enamel tray or plastic dish tub for sorting. Muffin tins or plastic ice cube trays work well to provide separate wells for members of each functional group as they are removed and classified. Small spatulas made with 1 mm Nitex work well. These are made by cutting

TABLE 20.2 Example of an actual Functional Feeding Group (FFG) data sheet for a macroinvertebrate sample from Rio dos Padres, State of Parana, Brazil.

Invertebrate Functional Group Assessment ~ Field Form

Stream: Rio dos Padres Reach: _____ Drainage: _____ Date: 2/16/05

Crew: Cummins, Merritt, et al. H_2O Temp: 21°C @ Time: 9:10 a.m.

Habitat Unit No.: 1 Habitat Type: Cobble

Sample Type (*circle one*): (Cobble) Wood Leaf Litter Fine Sediments Composite SAMPLE #: 1-____-____

Functional Group	Tally	Total	Identifiable Taxa
Shredders	𝍸 𝍸 𝍸 𝍸 III	23	Sericostomatidae = 1 *Gammarus* = 4 Gripopterygidae = 10 Calamoceratidae = 6 Leptoceridae = 2
Scrapers	𝍸 𝍸 𝍸 𝍸 𝍸 II	27	Psephenidae = 1 Helicopsychidae = 1 Blephariceridae = 21 Gastropoda = 1 Elmidae (adults) = 3
Filtering Collectors	𝍸 𝍸 𝍸 𝍸 𝍸	25	Hydropsychidae = 24 Simuliidae = 1
Gathering Collectors	𝍸 𝍸 𝍸 𝍸 𝍸 III	28	Baetidae = 10 Leptophlebiidae = 6 Elmidae (larvae) = 1 Chironomidae (not Tanypodinae) = 1 Leptohyphidae = 10
Predators	𝍸 II	7	Dytiscidae = 1 Gerridae = 1 Limnocorinae = 2 Corydalidae = 2 Anisoptera = 1

Sample Type (*circle one*): Cobble Wood Leaf Litter Fine Sediments Composite SAMPLE #: ____-__ __-____

Functional Group	Tally	Total	Identifiable Taxa
Shredders			
Scrapers			
Filtering Collectors			
Gathering Collectors			
Predators			

Sample Type (*circle one*): Cobble Wood Leaf Litter Fine Sediments Composite SAMPLE #: ____-____-____

Functional Group	Tally	Total	Identifiable Taxa
Shredders			
Scrapers			
Filtering Collectors			
Gathering Collectors			
Predators			

1-cm square pieces of 0.25 mm mesh Nitex, using hot glue to seal the borders, and placing a large drop of hot glue on one side into which the point of a dissecting needle is inserted to form a handle. These "bug spatulas" are particularly useful for capturing mobile mayfly and stonefly nymphs and work better than forceps. If the sample contains large numbers of small, very mobile invertebrates, such as *Baetis* mayflies, it may be preferable to simply make a total count in the pan or tray with a hand tally after the other animals have been removed. If invertebrate density in the sample is very high, it may be advisable to separate the sample into quarters for sorting. If equal effort is expended to remove large and small specimens, the total count of animals removed from a sample usually need not exceed 100 to obtain sufficient data to calculate FFG ratios.

Individuals are removed, assigned to an FFG using the keys (Appendix 20.1), and placed in the appropriate well in the muffin tin or ice cube tray. After sorting and separation are completed, the number of individuals in each FFG is tallied, and taxonomic notes are made on a field data sheet (see example in Table 20.3). Specimens then can be preserved in a Whirl-Pak with 70% ethanol, labeled, and returned to the laboratory for detailed taxonomic identification as desired. This more detailed taxonomy can be performed using texts and/or regional monographs, such as Sites and Polhemus (1994), Stewart and Oswood (2006), Thorp and Rogers (2016), Webb and McCafferty (2008), Wiggins (1998), and Merritt et al. (2008).

The seasonal timing of FFG sampling is critical, just as it is for any taxonomically based diversity study. It is important to sample when the greatest number of taxa are in feeding stages and are as large as possible; this serves both FFG and taxonomic analyses. Therefore periods of maximum egg laying, hatching, and adult emergence should be avoided. Because distinctive fall−winter and spring−summer communities of stream macroinvertebrates are common (Cummins et al., 1989; Maloney and Lamberti, 1995; Swan and Palmer, 2004), at least two samplings per year are required to adequately characterize the FFG composition. These seasonal differences may be driven by annual cycles in either temperature or precipitation. In general, the optimal sampling times are mid to late summer for characterizing the spring−summer populations and late fall to late winter for characterizing the fall−winter populations (e.g., Cummins et al., 1989).

Biomass data are preferable to numerical data in the FFG approach, but are much more time intensive to obtain. Biomass can be estimated in the field by measuring *biovolume*. A small graduated cylinder (5−10 mL, calibrated in 0.1 mL) can be used to determine volumetric displacement. The specimens in each FFG are added cumulatively to the graduated cylinder containing an initial known volume of water. The volume of water displaced by each FFG collection is recorded, and ecosystem surrogate ratios can be calculated using these volumes without conversion to actual estimates of biomass. However, biomass can be estimated in the laboratory from measurements of specimen lengths using length−mass relationships (e.g., Smock, 1980; Benke et al., 1999), as was done for the data in Table 20.4.

TABLE 20.3 Examples of Functional Feeding Group (FFG) ratios as indicators of stream ecosystem attributes.

Ecosystem Parameter	Symbols	FFG Ratios	General Criteria Ratio Levels[a]
Autotrophy to heterotrophy Index or gross primary production (P) to community respiration (R) Index	Auto/hetero or P/R	Scrapers to Shredders + Total Collectors	Autotrophic > 0.75
Coarse particulate organic matter (CPOM) to fine particulate organic matter (FPOM) Index	CPOM/FPOM	Shredders to total collectors	Normal shredder association linked to functioning riparian system *Fall−Winter* > 0.5 *Spring−Summer* > 0.25
FPOM in transport (suspended) (TFPOM) to FPOM in storage in sediments (deposited in benthos) (BFPOM)	TFPOM/BFPOM	Filtering collectors to gathering collectors	FPOM transport (in suspension) greater than normal particulate loading in suspension > 0.50
Substrate (channel) stability	Stable channel	Scrapers + filtering collectors to shredders + gathering collectors	Stable substrates (e.g., bedrock, boulders, cobbles, large woody debris) plentiful >0.50
Top−down predator control	Top−down control	Predators to total ALL other groups	Normal predator to prey balance 0.10−0.20

[a]*General ratio ranges given are for numerical or biomass data taken when most species are in mid to late larval instars or aquatic adults (see discussion under field sampling).*

TABLE 20.4 Example of Functional Feeding Group (FFG) ratios as indicators of stream ecosystem attributes.

Ecosystem Parameter	FFG Ratios	Calculated Ratios		General Criteria Ratio Levels	Evaluation
		Numbers	Biomass		
Auto/hetero or gross primary production/community respiration	Scrapers to shredders + total collectors	0.34	0.24	Autotrophic >0.75	Heterotrophic site, dependent on allochthonous organic matter inputs
Coarse particulate organic matter (CPOM)/fine particulate organic matter (FPOM)	Shredders to total collectors	0.32	0.64	Normal shredder association linked to functioning riparian system in summer >0.25	A summer shredder stream; species dependent mainly on slow processing rate of litter[a]
FPOM in transport (suspended) to FPOM in storage in sediments (deposited in benthos)	Filtering collectors to gathering collectors	0.87	1.76	FPOM transport (in suspension) enriched unusual particulate loading) >0.50	High FPOM loading (presence of Philopotamidae indicates very fine FPOM)
Stable channel	Scrapers + filtering collectors to shredders + gathering collectors	1.08	1.03	Stable substrates (e.g., bedrock, boulders, cobbles, large woody debris) plentiful >0.50	Channel stability high with numerous attachment sites for macroinvertebrates
Top−down control	Predators to total all other groups	0.22	0.14	Typical predator to prey balance 0.10−0.20	Typical predator to prey ratio

[a]*For example, see Cummins et al. (1989).*
Data from a second-order stream in the Allegheny National Forest, Pennsylvania, USA, during July.

20.2.3 Functional Group Designations

The key that appears below (Appendix 20.1) emphasizes higher-level taxonomic separations that permit reliable categorization of FFGs. The key is organized into the primary level of resolution, which normally provides an 85−90% or higher accuracy of FFG separation. After the key for the primary level of FFG assignment, the secondary level of resolution allows a number of exceptions. Reassigning these exceptions to the appropriate FFG can improve the level of accuracy 5% or more. For example, the mayfly nymphs of Isonychiidae have the body shape typical of gathering collectors. However, the nymphs have long setae on the inner margins of the fore tibiae that can be erected to form a filtering basket that traps FPOM, which classifies them as filtering collectors (Appendix 20.1, Key 5). Although the primary level of FFG assignment can be accomplished in the field with live material, identifying the exceptions often requires a hand lens or conducting the analysis in the laboratory with a dissection microscope. Another example is the organic case-bearing trichopteran *Brachycentrus*, which uses its forelegs as a filtering collector (Appendix 20.1, Key 2).

20.2.4 Functional Feeding Group Ratios as Surrogates for Ecosystem Attributes

Examples of FFG ratios used as indicators of stream ecosystem attributes are summarized in Table 20.3. The ratios can serve as indicators of the relative importance of stream autotrophy or heterotrophy, the size categories and relative amounts of CPOM and FPOM in transport and in storage, and the stability of the channel (e.g., coarse sediments, large wood, and rooted aquatic vascular plants). Examples of FFG ratios and their relationship to proposed thresholds, as well as interpretation of the predictions, are given in Table 20.4 for a stream in the state of Pennsylvania, United States. The use of FFG ratios as indicators of stream ecosystem attributes has been documented previously (e.g., Vannote et al., 1980; Minshall et al., 1983; Merritt et al., 1996, 1999, 2002; Mattson et al., 2014; Stone and Wallace, 1998; Wagner, 2001; Cummins et al., 2005, Andrade, 2004). Because the FFG method is responsive to changes in the macroinvertebrate food resource base (e.g., algae, litter, fine organics, prey), it is sensitive to both general and site-specific impacts in riparian zones and watershed land use. For example, the localized input of a toxic effluent in the form of DOM from a paper mill might be a

site-specific disturbance, while increased sediment or reduced litter inputs resulting from altered land use would be much broader.

Case study. The example shown in Table 20.4 for a second-order, heavily shaded, woodland stream in the Allegheny National Forest (Pennsylvania) includes ecosystem evaluations based on FFG ratios (Table 20.3). The FFG ratio that serves as a surrogate for the stream autotrophy/heterotrophy index, or P/R (P = daily gross primary production and R = daily total community respiration), indicates that the stream is distinctly heterotrophic (Tables 20.3 and 20.4; see also Chapters 28 and 34). That is, the in-stream biology is heavily dependent upon allochthonous organic matter from the riparian zone. The surrogate FFG P/R ratio reflects the low numbers and biomass of scrapers linked to periphyton primary production and the high abundance of shredders and collectors that use detritus of riparian origin as a food resource.

For collectors, FPOM food would be derived from shredder feeding on CPOM, (i.e., litter fragments or shredder feces) or directly from the terrestrial riparian soil-litter layer. Data in Table 20.4 were collected in July when significant numbers of summer shredders (Plecoptera: Peltoperlidae; Trichoptera: Lepidostomatidae) were present. The FFG surrogate ratio reflects the availability of appropriately conditioned leaf litter (i.e., suitable as a food for shredders; see Chapter 27). The ratio of CPOM relative to FPOM indicates that the system is a "spring−summer shredder stream" (Table 20.4; Cummins et al., 1989; Cummins, 2002). That is, summer shredders are dependent upon riparian plant litter that requires a long conditioning time, such as hemlock needles. This conditioning time, which can be up to 8 months or more for conifer litter (Cummins et al., 1989), is the period required for the plant litter to be colonized by stream microbes, especially aquatic hyphomycete fungi (see Chapter 10). The growth of shredders is dependent on the accumulated biomass of hyphomycete fungi in the matrix of the plant litter in streams where organic matter is of riparian origin (Hanson et al., 1985; Cargill et al., 1985; Grubbs and Cummins, 1994, 1996; Cummins, 2002). The general model for seasonal shifts in shredder dominance related to the type and timing of riparian litter inputs and the in-stream conditioning times required for each riparian plant species was developed from data for the North American temperate zone (e.g., Cummins et al., 1989; Cummins, 2002). However, the spring−summer alignment between shredder abundance and litter that requires long in-stream conditioning time likely is applicable to the tropics as well (e.g., Grubbs and Cummins, 1996; Forsberg et al., 2001; Wantzen et al., 2002; Cummins et al., 2005).

The FFG surrogate ratio for the availability of stream FPOM in transport (suspended load) relative to that in the benthos (bed load) indicates the availability of an abundant, good quality fine particulate food supply for filtering-collectors (Table 20.3). This surrogate ratio is consistent with the source of FPOM consisting of organic fragments derived from processed plant litter and organic soils from the riparian zone, sloughed attached periphyton, and macroinvertebrate feces (e.g., see gut contents of collector taxa in Coffman et al., 1971).

The FFG surrogate ratio for channel stability reflects the requirement of scrapers and filtering-collectors for nonshifting feeding and attachment surfaces, as opposed to the gathering-collectors and shredders that occupy the interstices of sediments and litter accumulations. The channel stability ratio indicates the availability of stable surfaces (Table 20.3) and supports the conclusion that the FPOM was derived from natural riparian and stream processes rather than land use impacts.

If the FFG ratio of predators to prey is in the expected range, it indicates that there is a balance at the stream site between prey species with long and short life cycles (Table 20.4). That is, a high top−down ratio (0.10−0.20) reflects the abundance of prey species having short life cycles and therefore populations that turn over rapidly to continuously renew the food supply for the longer-lived predators.

Thus in this example of the Pennsylvania stream (Table 20.4), the FFG ratios are consistent with the observations of the ecosystem properties at the sampling site and, by inference, this second-order stream as a whole. Additional examples of the use of FFG ratios as surrogates for these stream ecosystem attributes can be found in Merritt et al. (1996, 1999, 2002), and Mattson et al. (2014) for south Florida rivers, Cummins et al. (2005) for streams in southeast Brazil, Masese et al. (2014) for highland streams in Kenya, and Thanee and Phalaraksh (2012) for anthropogenically disturbed streams in Thailand.

20.3 SPECIFIC METHODS

20.3.1 Basic Method 1: Determining Macroinvertebrate Functional Feeding Groups in the Field

1. Establish sampling teams of two or three individuals.
2. Each team should take at least one sample from each of the three general habitat types (rock, litter, and fine sediments) using a D-frame or large aquarium net with a mesh size of 0.50 mm or finer. If the habitats are to be evaluated

independently, the samples should be analyzed separately and a stream reach-scale evaluation performed by combining the data later. For a faster, but less detailed, exercise that provides a reach estimate only, samples from the habitats can be combined before sorting. If other habitats are present (e.g., rooted macrophytes, LWD), they should also be sampled or included in a composite sample. The minimal goal is to have each team produce three FFG ratios, one for each habitat type, or one ratio if habitat samples are pooled before sorting (Table 20.2).

3. Special care is required when sampling cobble from riffles to note any caddisfly (Trichoptera) nets that are present. The nets are diagnostic for some caddisfly larvae but are destroyed during sampling and the larvae will be moving about freely and can be confused with nonnet spinning, free-ranging predaceous caddisfly larvae (family Rhyacophilidae).
4. Wash the sample to be sorted (i.e., invertebrates to be removed) into the white enamel tray or plastic dish tub. Ensure that the sample is covered with 2–4 cm of water. Leaves, large pieces of wood, cobble, and gravel can be washed off separately into the tray with a squeeze bottle to remove invertebrates and discarded the cleaned substrates to facilitate sorting. If the sample is to be returned to the laboratory for analysis, transfer it to a Whirl-Pak bag containing a label (pencil on sturdy white paper) with sampling team designation, date, stream site, habitat or composite sample type, and an identification number that can be referenced to any field notes taken. Preserve the sample with 70% ethanol (if samples contain significant water, then a higher concentration of ethanol will be needed). Skip to Section 20.3.3.
5. Remove invertebrates from the sample with forceps and/or the bug spatula described above and separate them by functional group using the FFG key (Appendix 20.1), into separate wells of the muffin tin or ice cube tray for enumeration.
6. Count the total number of organisms in each FFG (this will be facilitated by the use of a hand counter; see example in Table 20.2). Using a hand calculator, determine the FFG ratios for each of the habitat types, or for the total if the sample is a composite, following the format shown in Table 20.3.
7. Interpret the ratio data relative to the expected threshold levels (Table 20.3) as shown in the example in Table 20.4. This allows the ecosystem condition for each habitat or the stream reach as a whole to be evaluated from a composite sample or by combining habitats. If there are multiple teams, all data should be combined and means calculated for each habitat and reach to allow for a general assessment of stream ecosystem conditions. See Chapters 2 and 38 if a more extensive physical habitat assessment is to be combined with the FFG analysis.

20.3.2 Advanced Method 1: Optional Field Exercise

1. After steps 1 through 5 earlier, determine the biovolume of each functional group (i.e., a composite of all individuals in each group) using a graduated cylinder. This transfer will require the use of fine point (jeweler's) or BB forceps.
2. Complete steps 6–7 from *Basic Method 1* using volume measures as well as the numerical data.
3. Evaluate the differences in the ratios and assessments of ecosystem condition when numerical and biovolume data are compared.

20.3.3 Basic Method 2: Determining Macroinvertebrate Functional Feeding Groups in the Laboratory

1. If samples are taken and preserved in the field, as described in step 4 of the field procedure above, empty the contents of a Whirl-Pak into a petri dish.
2. Remove invertebrates from the sample and assign them to FFGs using a dissecting microscope. Carefully examine the macroinvertebrates for exceptions to the primary level of separations (Appendix 20.1). Then, identify specimens in each FFG to genus, or lowest possible taxonomic level, using Merritt et al. (2008) and Thorp and Rogers (2016). The ecological tables in Merritt et al. (2008) should be used to further refine the functional group separations.
3. Complete steps 6 through 7 from *Basic Method 1*.

20.3.4 Advanced Method 2: Optional Laboratory Exercise

1. After the specimens are sorted, identified, and categorized into FFG in the laboratory, measure and record the length of each specimen to the nearest millimeter under a dissecting microscope, using a clear plastic millimeter ruler placed on the microscope stage under the petri dish, or with a calibrated ocular micrometer.

2. Convert the length of each specimen to an estimate of its dry biomass using the regression equations in Smock (1980) and Benke et al. (1999).
3. Complete steps 6 through 7 from *Basic Method 1* using the calculated dry biomass data.

20.4 QUESTIONS

1. How could the timing (i.e., season) of your sampling have influenced your estimates of FFG ecosystem surrogate ratios and the interpretation of ecosystem conditions?
2. When and why would FFG ratios calculated on the basis of biomass yield a better estimate of FFG invertebrate community structure than numbers of individuals?
3. How would community structure, as indicated by FFGs, be influenced by changes in riparian cover (e.g., timber harvest)? For example, how would an increase in incident radiation reaching the stream and loss of litter inputs affect FFG ratios?
4. Would FFG analysis be a more useful metric than a diversity index in assessing the effects of sewage effluent on a stream macroinvertebrate community? If not, why?
5. In the analysis of the selected stream, which group of collectors (filtering or gathering) was most abundant? Speculate as to why.
6. What are some of the advantages and disadvantages of the use of FFG ratios, as compared to other aggregate measures such as diversity indices or the index of biotic integrity? What inaccuracies result from just using individual taxonomic identifications?
7. Many macroinvertebrate rapid bioassessment methods specify riffle sampling only. Considering the focus of the FFG method, what would be missed by such an approach?

20.5 MATERIALS AND SUPPLIES

Field Materials and Supplies

70% and 95% ethanol
Hand calculator
White enamel sorting trays or plastic dish tubs
"Bug spatulas" (see earlier)
Fine point (jeweler's) or BB forceps
Graduated cylinders: 1 mL graduated in 0.01 mL divisions, and 5 and 10 mL graduated in 0.1 mL divisions)
Hand lens
Hand tally counter
D-frame or large aquarium net (0.50 or 0.25 mm mesh)
Multiple-compartment container (muffin tins or ice cube trays) for separating specimens into FFGs before counting
Whirl-Pak bags (or sample bottles)
Label material (3 × 5 cards), scissors, and # 2 pencils

Laboratory Materials and Equipment

Dissecting microscope
Clear plastic ruler (millimeter graduations) or ocular micrometer
Petri dishes
Taxonomic guides (e.g., Merritt et al., 2008; Thorp and Rogers, 2016).

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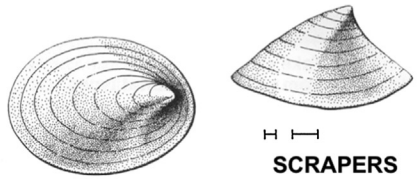
APPENDIX 20.1 KEY TO THE FUNCTIONAL FEEDING GROUPS OF LOTIC MACROINVERTEBRATES

KEY TO FUNCTIONAL FEEDING GROUPS

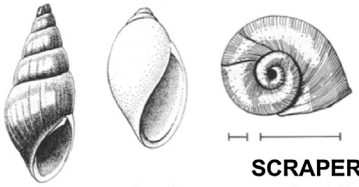
Indicates size or range of sizes

1. ANIMALS IN HARD SHELL (Phylum Mollusca)
   a. LIMPETS (Class Gastropoda)



SCRAPERS

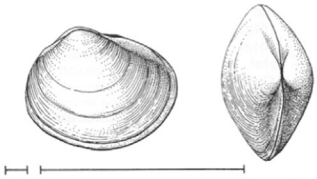
   b. SNAILS (Class Gastropoda)



SCRAPERS

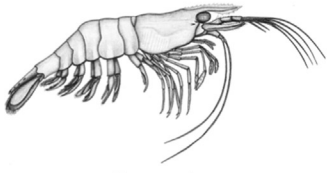
Snails are generalized (facultative) feeders and can also function as Shredders.

   c. CLAMS OR MUSSELS (Class Pelecypoda)



FILTERING COLLECTORS

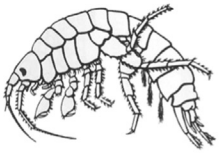
2. SHRIMP-LIKE ANIMALS (Class Crustacea)



Decapoda

Isopoda

SHREDDERS



Amphipoda

Can also function as facultative Gathering Collectors

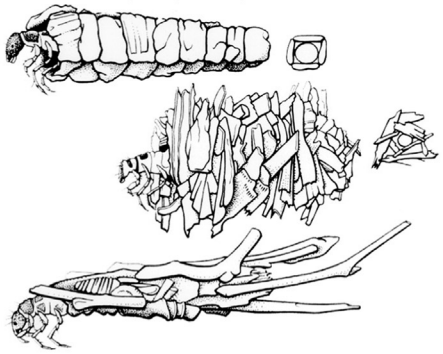
3. LARVAE IN PORTABLE CASE OR "HOUSE".	Go to KEY 2
4. LARVAE IN FIXED RETREAT WITH CAPTURE NET. *Note:* Care must be taken when collecting to observe nets	Go to KEY 3
5. WITHOUT CASE OR FIXED RETREAT.	
a. WORM-LIKE LARVAE, WITHOUT JOINTED LEGS.	Go to KEY 4
b. NYMPHS OR ADULTS WITH JOINTED LEGS.	Go to KEY 5
6. DOES NOT FIT KEY 5 EXACTLY.	Go to KEY 6 or KEY 7

KEY 2

FIRST LEVEL OF RESOLUTION

LARVAE IN PORTABLE CASE
Caddisflies (Order Trichoptera)

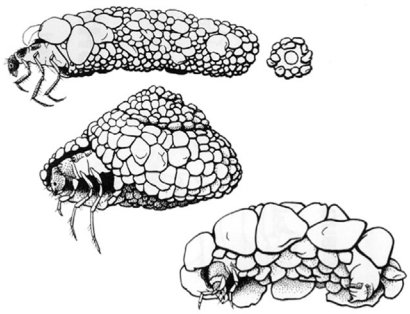
CASES, ORGANIC
Leaf, stick, needle, bark



Families Limnephilidae (in part)
Lepidostomatideae (in part) Phyrganeidae,
Leptoceridae (in part)

SHREDDERS

CASES MINERAL
Sand, fine gravel



Families Glossosomatidae,
Limnephilidae (in part), Helicopsychidae

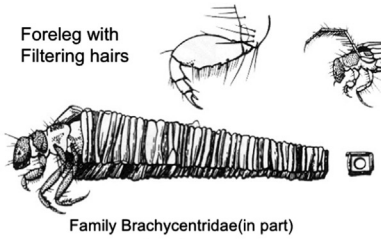
SCRAPERS

SECOND LEVEL OF RESOLUTION considers a few fairly common caddisflies that would be misclassified above on the basis of case composition alone.

CASES ORGANIC

Cases square in cross section and tapered, with no bark or flat leaf pieces included. Front attached to substrate. Larvae extend legs and filter the current

Foreleg with
Filtering hairs



Family Brachycentridae(in part)

FILTERING COLLECTORS

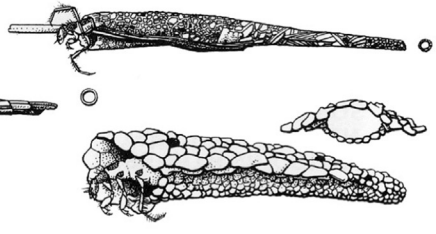
Cases long, slender and tapered, made of plant material

Family Leptoceridae (in part)

GATHERING COLLECTORS

CASES MINERAL

Cases long, slender and tapered (mostly fine sand) or cases ovoid and very flat in cross section



Family Leptoceridae (in part)

GATHERING COLLECTORS

KEY 3

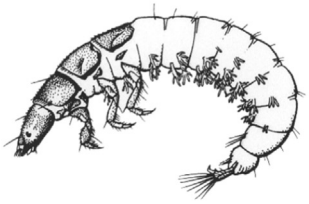
FIRST LEVEL OF RESOLUTION

LARVAE WITH FIXED RETREAT AND CAPTURE NET
Note: Care must be taken when collecting to observe nets.

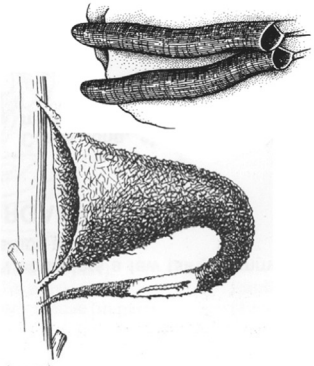
Caddisflies (Order Trichoptera)

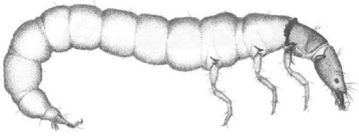
True Flies (Order Diptera)

COURSE NET IN "SCAFFOLDING"

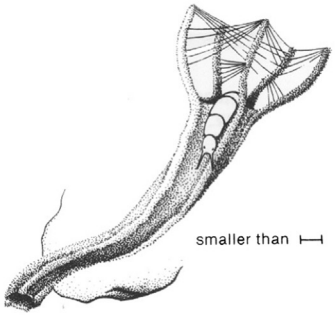


FLATTENED SOCK-LIKE OR TRUMPET-SHAPED NET OF FINE MESH





TUBE WITH SILK STRANDS STRUNG BETWEEN TERMINAL PRONGS



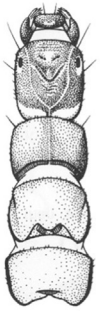
True Midges (Family Chironomidae)

Families Hydropsychidae, Philopotamidae, Polycentropodidae

FILTERING COLLECTORS

SECOND LEVEL OF RESOLUTION separates from free living larvae those net spinning caddisflies that may have been inadvertently collected without being associated with their nets.

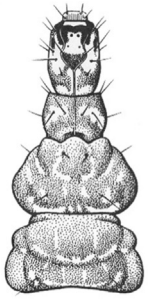
NET SPINNING CADDISFLIES
Frequently separated from their nets



HEAD AS WIDE AS THORAX
Especially Philopotamidae (bright yellow) and Hydropsychidae (bright green or brown)

FILTERING COLLECTORS

FREE LIVING CADDISFLIES
Non net spinning



HEAD LONG, SMALL, AND NARROWER THAN THORAX

Rhyacophilidae (often bright green)

PREDATORS

KEY 4

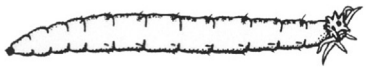
FIRST LEVEL OF RESOLUTION

WORM-LIKE LARVAE WITHOUT JOINTED LEGS

LARGE

Larger than

Head retractile and poorly developed
Caudal lobes with eye-like spiracles



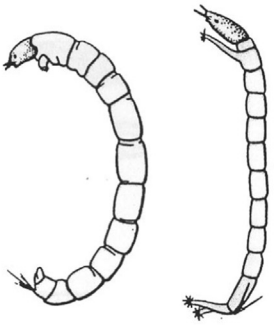
Craneflies (Family Tipulidae (in part)

SHREDDERS

SMALL

smaller than

LONG AND SLENDER



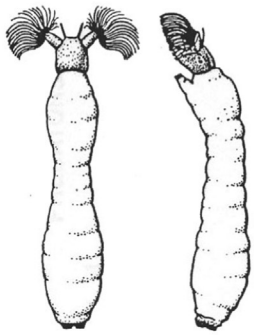
True Midges (Family Chironomidae)

Note: Subtract 10% of count for Predators

GATHERING COLLECTORS

BOWLING PIN SHAPE

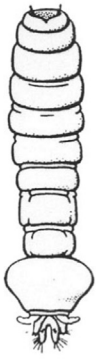
Bulbous base usually fastened tightly
to substrate



Blackflies (Family Simuliidae)

FILTERING COLLECTORS

SECOND LEVEL OF RESOLUTION considers some worm-like Predators that would be misclassified in the above key.



LARGE

Posterior segment swollen
Head retractile

Family Tipulidae (*Eriocera* type)

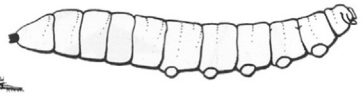
WORM-LIKE LARVAE WITHOUT
JOINTED LEGS

SMALL

Prolegs along entire length
Head visible

Family Athericidae

Prolegs poorly developed
or absent; jaws well
developed; very active



Family Tipulidae (*Dicranota* type)

PREDATORS

KEY 5

FIRST LEVEL OF RESOLUTION

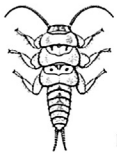
NYMPHS WITH JOINTED LEGS

3 (or 2) TAILS (FILAMENTS) AT BACK
NO EXTENDIBLE LOWER LIP (LABIUM)

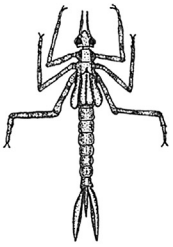
3 FLAT PADDLES OR POINTS AT BACK
EXTENDIBLE LOWER LIP

3 (or 2) TAILS WITH LATERAL ABDOMINAL GILLS.
Mayflies (Order Ephemeroptera)

2 TAILS WITHOUT LATERAL ABDOMINAL GILLS.
Stoneflies (Order Plecoptera)

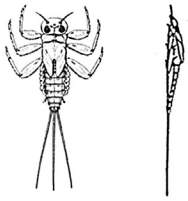


3 FLAT PADDLES AT BACK



POINTS AT BACK

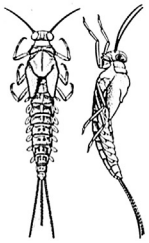
Body shape ovoid.
Flat in cross section.



Families Heptageniidae, Ephemerellidae (in part)

SCRAPERS

Body shape cylindrical.
Round in cross section.



Families Baetidae, Leptophlebiidae, Ephermerellidae (in part), Ephemeridae

GATHERING COLLECTORS

Bright color pattern.
Very active.

Setipalpian Stoneflies

PREDATORS

Dull brown or black sluggish

Filipalpian Stoneflies

SHREDDERS

Damselflies
(Suborder Zygoptera)

PREDATORS

Dragonflies
(Suborder Anisoptera)

PREDATORS

KEY 6

SECOND LEVEL OF RESOLUTION considers some fairly common insects that do not fit in the above key or would be misclassified on the basis of body shape alone.

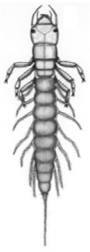
LARVAE, NYMPHS, OR ADULTS WITH JOINTED LEGS WITHOUT CASE OR FIXED RETREAT

WITH LONG TAIL(S) OR CAUDAL HOOKS

CAUDAL HOOKS

Family Corydalidae

1 TAIL (FILAMENT)



Family Sialidae

PREDATORS

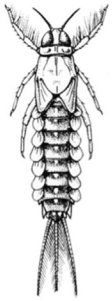
3 LONG CERCI

Body shape ovoid
Rear end often erected
scorpion-like when disturbed

Family Ephemerellidae (in part), Caenidae, Tricorythidae

GATHERING COLLECTORS

Body shape cylindrical.
Long hairs on inside of front legs.

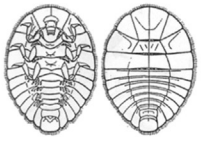


Family Isonychiidae

FILTERING COLLECTORS

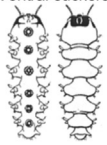
WITHOUT LONG TAILS.
Beetles (Order Coleoptera)

With ventral suckers or disc shape.
Head and legs totally concealed beneath.



Water Pennies
(Family Psephenidae)

(Order Diptera)
Lobed body.
Ventral suckers.



Family Blephariceridae

SCRAPERS

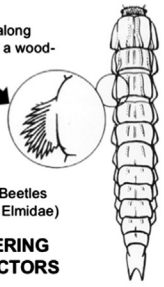
Adult beetle

Riffle Beetles
(Family Elmidae)

SCRAPERS

Slender, larvae, triangular in cross section

If larva has spines along lateral margins, it is a wood-eating Shredder



Riffle Beetles
(Family Elmidae)

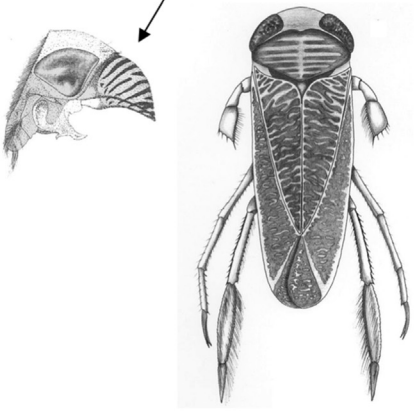
GATHERING COLLECTORS

KEY 7

SECOND LEVEL OF RESOLUTION considers some fairly common insects that do not fit in the above key or would be misclassified on the basis of body shape alone.

NYMPHS AND ADULTS
WITH BEAK AND HEMELYTRA

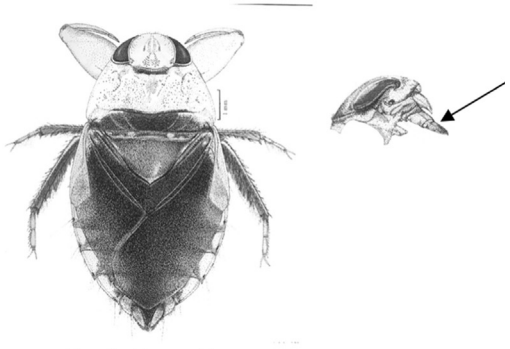
Beak triangular
front legs smaller



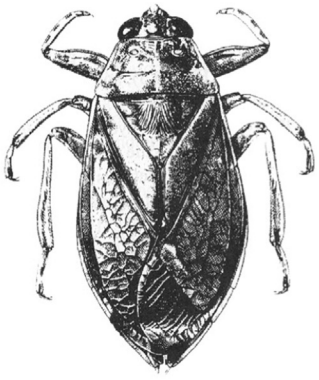
Family Corixidae

SCRAPERS

Sharp beak,
front legs large



Family Naucoridae



Family Belostomatidae

PREDATORS