Analysis of long-term benthic data for the Pelagic Organism Decline investigation

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For this analysis, we used data from the four IEP-EMP long-term benthic monitoring stations: D28A in Old River at Rancho Del Rio, D4 on the Sacramento River above Point Sacramento near the confluence with the San Joaquin, D7 in Grizzly bay, and D41A in the shallows of San Pablo Bay (Fig.1). Sampling at D28A, D4 and D7 occurred monthly from June 1980 to October 2003 and quarterly in 2004-2005. Annual to biannual sampling occurred at these three stations from 1975 to 1979. Monthly sampling begun at D41A in summer 1991 and shifted to quarterly in October 2003. Before that D41A was sampled annually in 1975-76 and 86, and four to six times a year in 87-90 (By the USGS). It is to be noted that when only one or two samples where available for the year the resulting yearly average is more biased than when quarterly or monthly data where available.

For this analysis we summarized total organisms abundance, species richness and species diversity (using Shannon's H' index) monthly and yearly. We plotted the monthly relative abundance of the 20 to 25 dominant species that constitute 95% or more of the total abundance at each site. We also summarized the monthly relative abundance of all species grouped as suspension feeders, deposit feeders, or mixed feeders. We performed ordinations on the yearly average of species abundance using Bray-Curtis dissimilarities and non-metric multidimensional scaling. The EMP does not measure or weigh benthic organisms and thus the biomass information necessary to assess phytoplankton grazing rates was not available to us.
We also summarized the relevant environmental data that were available monthly for the period 1975-2005. Variables included: sediment granulometry and organic matter content from EMP's benthic monitoring; flows from DAYFLOW; Chlorophyll a, nitrogen, phosphorus, salinity, and secchi depth from EMP's water quality monitoring.

In this summary we focus on the period 1993 – 2004, to determine whether there is any change in the benthos that predates or matches the step change in pelagic organisms' abundance that occurred circa 2001. However, we also relate any changes that occurred during this period to changes that occurred during the drought years of 1987 – 1992.

D28A-L, in Old River

Abundance, species richness and diversity: Total abundance of organisms (Fig.2) declined in 1999 and, during 2000-2004, yearly average abundance remained at about half of what it was during the 1993-1998 period. Only 1977 and 1989 had somewhat lower average abundance (Figure 2). Average species richness declined from about 20 species during 1993-1998 to 15 in 1999, 2001 and 2002. In 2003-2004 it was back close to 20 (Fig. 2). Average number of species/sample in 1989 was 11.2. Diversity has remained high throughout 1994-2004. Overall, a community change occurred starting in

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1999 and all three indicators reached a low in 2001. However this community change was not as drastic as that of 1987-1989, especially in terms of diversity.

Benthic assemblage: Benthic assemblage composition began shifting in 1999 (Fig. 3). Before that, the period 94-98 was characterized by about 50% of mixed feeders (in particular the polychaetes *Manyunkia speciosa, Laonome sp.* and the corophiid amphipods *Americorophium stimpsoni* and *A.spinicorne*), 25-30% of deposit feeders (mostly tubificid worms such as *Varichaetadrilus angustipenis* and the gammarid amphipod *Gammarus daiberi*); and 20-25% of suspension feeders (almost exclusively the bivalve *Corbicula fluminea*). Each of these 3 groups constituted about 1/3 of the community in 1999 and since then the proportion of deposit feeders has been increasing to reach 70% in 2004. Among the deposit feeders, the ostracod *Cyprideis sp.a*, first identified in the estuary in 1992, has become numerically important in the assemblage (though very small in individual size) since 2002. In 2003-2004 the proportion of suspension feeders is only 10-15%. The abundance of the bivalve *Corbicula fluminea* (the main suspension feeder at D28A) in 2000-2004 is slightly lower than during 1994-1997, and overall is at its lowest abundance since 1985-86. *C. fluminea* was 2 to 3 times more abundant in 80-83 (when it constituted about 50% of the assemblage numbers) and again in 88 to 93 (40-70% of the assemblage).

In summary, during the 1993-2004 period, the benthic community has shrunk in size since 1999 with no big loss of diversity but a shift from mixed feeders toward deposit feeders. Suspension feeder *C. fluminea*, after a moderate increase in numbers in 98-99, has declined back to the low relative abundance level seen in 1994-1997 (Fig.4).

Sediment composition: Sediment granulometry (Fig.2) was variable throughout the study period. Gravel is rare and was found infrequently in 1980-1984 and in 1999-2003. Sand or fines (silt and clay) may represent up to 85% of the mineral portion of the sediment. Sandier periods include 1980-1985, 1990, 1993, and 1998-2004. Percent organic content is variable but appears to be higher on average during periods of finer sediments. It can be as high as 15-20% but typically a large portion is peat which is not a good source of food for benthic organisms.

Hydrology: River flow at D28A switches direction with the tide (USGS data, not show in Figs), but overall the water is consistently going south toward Clifton Court Bay. North bound discharge occurs only during periods of exceptionally high flows from the San Joaquin River: during the period 1987-2004 it occurred in May 1993, March-May 1995, Feb-March 1996, Jan-March 1997, Feb-June 1998 and February 1999. Periods of years with high flows from the San Joaquin River (Fig.2) reaching up to the D28A site, correspond to years with overall greater abundance, high diversity and larger proportions of organisms that are mixed feeders.

Water environment: Chlorophyll a concentrations (Fig.2) indicates that phytoplankton blooms occurred regularly during 1980-1988. Since then chlorophyll a concentrations have remained below 10 µg/L except for 1993 and a couple of times in 1999 and 2000.

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Secchi depth has been generally been increasing at this station over the study period 1977-2004. Salinity is consistently very low at this station.

D4-L, in Sacramento River near the confluence.

Abundance, species richness and diversity: Total abundance of organisms (Fig.5) declined in 2001 to the second lowest value in record (the lowest occurred in 1996). But overall average yearly abundance during the period 2000-2004 was the same as that of the period 1987-2004. Previously, in 1980-1986, populations at this site had been 2 to 4 times larger. Average species richness declined to an average of 15 species/sample in 1999 from a high of 21.5 in 1998. During 2001-2004 species richness was lower than in the 1992-1998 period, but somewhat higher than during 1980-1989 (Fig. 5). Diversity started declining in 1999, reaching a low in 2002-2003 that matched the historic low diversity of 1988-1989. Previous to that diversity had been at its highest in record from 1992 to 1998.

Benthic assemblage: During the first part of record, in 1975 and 1979-1986, the composition of the benthic assemblage at D4 (Fig.6) was dominated numerically by mixed feeders (in particular the corophiid amphipods *Americorophium stimpsoni* and *A.spinicorne*) which constituted 60 to 80% of the community; deposit feeders (the tubificid worms *Limnodrilus hoffmeisteri* and *Varichaetadrilus angustipenis*, and the spionid worm *Boccardiella ligerica*) and suspension feeders (the bivalve *Corbicula fluminea*) constituting each 5 to 25% (Fig.6). The exception to this early period is the drought year 1977 where about 80% of a much reduced community was made of the deposit feeder *B. ligerica*, the rest being constituted of the amphipod *Grandidierella japonica* (usually found in the brackish Grizzly and San Pablo Bays) and very few *C. fluminea*. 1978 was a recovery year for the community.
The next period begins with the invasion by the Asian clam *Corbula amurensis* in 1987, followed by two years 1988-1989 where the benthic community resembles that of 1977: small, almost completely dominated numerically by *B. ligerica* (80 to 90% of the total count) and a small proportion of bivalves. During the rest of the drought years (until 1992) the community diversity increased, including significant proportions of the polychaete *Laonome sp.* (introduced in 1989), the cumacean *Nippoleucon hinumensis* (introduced in 1986), and the gammarid amphipod *Gammarus daiberi* (introduced in 1981).
The return of higher flows in 1993 introduced a period (1993-1999) of a very diverse community with the return of tubificid worms (principally *Varichaetadrilus angustipenis* and *Bothrioneurum vejdovskyanum*) and of the corophiid amphipods *Americorophium stimpsoni* and *A.spinicorne*. Among the bivalves *C. fluminea* numbers increased while *C. amurensis* abundance declined to a very low proportion of the community.
In the recent period 2000-2004, the community remained similar to that of the previous one, despite a marked decrease in species richness and diversity. Tubificid worms (*V. angustipenis*) numbers were reduced, *C. fluminea* abundance decreased also while that of *C. amurensis* increased reaching in 2004 levels similar to 1991-1992 (Fig.7).
Interestingly, while the corophiid amphipod *Americorophium stimpsoni* has almost

disappeared from the assemblage since 2000, its congener *Americorophium spinicorne* (also believed to be a native organism) is now dominant (up to 80% of the assemblage in 2002-2003) and persistent in the assemblage. According to our data *A. spinicorne* has a higher salinity tolerance than *A. stimpsoni*, and appears to tolerate the seasonal salinity excursions (up to 6 or 8 psu) that have been common in the 2000-2004 period (Fig.5). It is important to recognize, that even though the assemblage composition at D4 has shifted back toward amphipods, the overall amphipod population density is less than it had been in the 70's and 80's, when benthic populations were much larger that they have been since 1987.

In summary, during the 1993-2004 period, the benthic community has lost species richness and diversity after 1999, indicating a stress on the community, while maintaining overall population size. Since then the community has remained similar to that of 1993-1999 with a shift towards species with somewhat higher salinity tolerance such as *C.amurensis* and *A. spinicorne*. However, the changes observed are much less drastic than those that occurred in 1987-1988 when amphipods and tubificid worms almost disappeared from the assemblage.

Sediment composition: Sediment granulometry (Fig. 5) was variable throughout the study period. Gravel is extremely rare, it was found only 3 times in the early eighties. Sand or fines (silt and clay) may represent up to 95% of the mineral portion of the sediment. Periods with predominance of fines include 1983, 1992-1999 and 2001. Percent organic content varies widely but appears to be less variable during periods of finer sediments. It can be as high as 50-60% but in these cases a large portion is peat which is not a good source of food for benthic organisms. Since 2000, the variability and average percent organic matter in the sediments has been variable but increasing.

Hydrology: Sacramento River flows at Rio Vista (from Dayflow) are the closest of available flow data (Fig.5). Some correlations seem to occur between flows at Rio Vista and percent of fines in the sediment. Much clearer relationships are apparent between flow at Rio Vista and salinity at D4.

Water environment: Chlorophyll a concentrations (Fig.5) indicates that phytoplankton blooms occurred regularly during the period 1975-1986. Since then chlorophyll a concentrations have remained below 10 µg/L except for 1993. It is interesting to note that the period of higher phytoplankton blooms is also a period when the benthic community was more numerous overall (Fig. X) and when clam (*C. fluminea*) abundance was as great or greater than it has been since 1987.
There is no trend in Secchi depth at this station over the study period 1975-2004. Salinity is usually low at this station. A large increase occurred in 1976 culminating in 1977 at 6 to 8 PSU over most of the year, this increase explains the drastic change in benthic assemblage and extremely low *C. fluminea* that year. Salinity increased again in 1987, reaching a peak in 1988 and another in 1991. This resulted in another drastic change in community. This time *C. Amurensis* (which is more salt tolerant than *C.fluminea*), invaded and partially made up for the large decrease in *C. fluminea* abundance. Since 2000, although the average salinity has not reached high values as in

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these previous cases, late season salinities have reached again up to 6 to 8 psu, this may be enough to explain the recent shifts in assemblage as discussed above.

D7 in Grizzly Bay

Abundance, species richness and diversity: Total abundance of organisms (Fig.8) has steadily increased over 1999-2003 and decreased slightly in 2004. The period 1993-1994 had much lower total abundance, except for 1993. Abundance of the past few years is similar to that of the period 1987-1992. The year 1984 has seen the highest abundance on record, and the years 1978-1979 the lowest.
Species richness and diversity have been stable since 1999, after a period of year-to-year ups and downs during 1993-1998. Before that, species richness and diversity had been steadily increasing over the period 1980-1986 and both decreased drastically over the years 1987-1989, indicating a large disturbance of the benthic assemblage. From 1990 to 1993 these 2 indicators went back up to a level similar to that of recent years.

Benthic assemblage: Although we have only two samples for 1977, the benthic assemblage that year (Fig.9) is clearly composed of species usually found in San Pablo Bay: the gammarid amphipod *Ampelisca abdita*, the corophiid amphipod *Monochorophium acherusicum*, and the spionid polychaete worm *Streblospio benedicti*. Water salinity (Fig.8) remained very high (between 12 and 16 psu) throughout 1977.
Benthic populations in 1978-1979 were very small and comported organisms such as the bivalve *Macoma petalum* and the polychaete worm *Neanthes succinea*. Benthic populations remained small in 1980-1981, dominated by the tubificid worm *Limnodrilus hoffmeisteri* and the bivalves *M. petalum* and *Mya arenaria.*
The period 1983-1984 brought extremely fresh conditions to Grizzly Bay, the population increased to the largest on record and was dominated by species usually found at the confluence: the amphipod *Americorophium stimpsoni*, the bivalve *Corbicula fluminea*, and the tubificid worms *L. hoffmeisteri* and *Varichaetadrilus angustipenis.* In 1985-1986 the population was reduced as salinity increased, *C. fluminea* was replaced *M. arenaria*, and *A. stimpsoni* by the introduced amphipod *Corophium alienense* and the introduced cumacean *Nippoleucon hinumensis*. Species richness and diversity reached a high in 1986.
The next period began with the invasion by the Asian clam *Corbula amurensis* in 1987, which reached very high abundance immediately. That same year it constituted 75% of the assemblage, and it reached 95% in 1988. During the rest of the 1987-1992 period the assemblage saw a moderate increase in diversity, including larger proportions of *N. hinnumensis, C. alienense*, and of the barnacle *Balanus improvisus.*
The period 1993-2004 is characterized by two types of assemblages. During the high flow years of 1995, 1996 and 1998 the population is reduced but more diverse: *C. amurensis* is less dominant, the amphipods *A. stimpsoni* and *Gammarus daiberi* are present alongside other species. Other years in that period have a more abundant although less diverse community assemblage constituted of 40 to 70% *C. amurensis*, a large proportion of *C. alienense* (especially so since 2000), *N. hinnumensis*, the spionid polychaete *Marenzelleria viridis* (introduced in 1992) and not much else.

In summary, the present assemblage is the result of invasions that occurred in the mid to late eighties, after major perturbations to the benthic community in 1977 and in 1982-1984. Since 1994 the assemblage has remained consistent except in high flow years such as 1995-1996 and 1998. It is interesting to note though that the bivalve population of *C. amurensis*, which had been reduced overall by these three high flow years over the period 1994-1999, is since 2001 back to high levels similar to those reached in 1988-1989 (Fig. 10).

Sediment composition: Sediment granulometry (Fig. 8) was very uniform throughout the study period. Sand is extremely rare and fines (silt and clay) represent typically 100% of the mineral portion of the sediment. Percent organic content has been seasonally invariable, declining slowly from 8 to 7% from 1977 to 1999, and falling to roughly 5% in the middle of 1999.

Hydrology: Delta outflow (from Dayflow) are the closest of available flow data estimates. Relationship between delta outflow and salinity at D7 are apparent (Fig.8).

Water environment: Chlorophyll a concentrations (Fig.8) indicate that phytoplankton blooms occurred regularly during the period 1975-1986. Since then chlorophyll a concentrations have remained at or below 10 µg/L except for one month in 2000. It is interesting to note that the largest phytoplankton blooms occurred in 1978-1980 when the benthic community was extremely reduced and the number of bivalve suspension feeders almost nil.
There is no trend in Secchi depth at this station over the record period 1975-2004.
Salinity can be extremely variable at this location. Some years it remains constantly high like in 1977 when it staid above 12 psu, or constantly low like in 1983 when it did not go much above 1 psu. Other years salinity varies widely like in 2001 (from 0.2 to 13.8 psu).

D41A in the shallows of San Pablo Bay

Abundance, species richness and diversity: The period of record at this station is 1975-2004, but prior to 1991, sampling was conducted infrequently: one sample in 1975, one in 1976, and seasonal samples were collected 1986-1990 by USGS for the RMP program(Fig.11).
Total abundance was higher on average during the period 2000-2004 than during the years 1995-1999. Populations in 1993-1994 were bigger than in 1995-1999. Previous to that, there is good indication that1989 and 1991 had large populations, although we have only 5 and 7 samples for these years.
Species richness was high (22-26 species per sample on average) from 1987 to 1991, declined in 1992-1993 and remained at an average of 12-15 species per sample until 2000. It has bee increasing since 2001, reaching an average of 23 species per sample.
Interestingly, diversity did not vary in synchrony with species richness, like at other stations. Overall it remained at similar levels throughout the period of record. This is the result of two species being alternatively very dominant in the assemblage.

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Benthic assemblage: In the single samples for 1975 and 1976 (Fig.12), the amphipod *Ampelisca abdita* was very dominant, accompanied by the bivalve *Gemma gemma*, the spionid polychaete worm *Streblospio benedicti*, and the corophiid amphipod *Monocorophium acherusicum*.
The single sample taken in 1986 was dominated by *A. abdita*, and the bivalve *Mya arenaria*, and shows the arrival of the introduced cumacean *Nippoleucon hinnumensis*.
Five samples taken in 1987 show *A. abdita* very dominant and accompanied by the bivalves *Musculista senhousia* and *M. arenaria*, and the arrival of the introduced amphipod *Corophium heteroceratum* and the introduced bivalve *Corbula amurensis.*
In 1988 and 1989 (with 6 and 5 samples) we saw *C. amurensis* become co-dominant with *A. abdita*, and detected the arrival of the introduced amphipod *Corophium alienense*.
Since 1990, two types of benthic assemblages are found:

- Years (1990-1992, 1994, 2001-2004) with larger populations, where *A.abdita* is numerically extremely dominant (65 to 90% of the assemblage), *C.amurensis* constituting only 5 to 20% of the total, and *N.hinumensis*, *M. acherisicum* and *C. alienense* reaching small but notable proportions. Years falling in this type have high salinities (Fig.11), between 20 and 30 psu.
- Years (1993, 1995-2000) with generally smaller populations, where *A.abdita* is not as numerically dominant (30 to 55% of the assemblage), *C.amurensis* constituting 20% to 55% of the total, *N.hinumensis* reaching up to 20% of the population, and very small proportions of other species. Years with this community type are higher outflow years with somewhat reduced and much more variable salinities. Years 1993 and 2000 are transition years, also both had very high numbers of bivalves.

It is to be noted that whether the benthic assemblage is almost completely dominated by *A. abdita* or whether it is co-dominated by *A. abdita* and *C. amurensis*, the assemblage is numerically dominated by suspension feeders since both species share the suspension feeding habit. However, *C. amurensis* is generally larger in size. Also *A. abdita* is more numerically dominant when the overall population is larger, which means that bivalve numbers are not necessarily smaller during years with reduced salinities (Fig.13).

In summary, the present assemblage is co-dominated by an introduced bivalve (*C.amurensis*) and an amphipod believed to be native (*A. abdita*), both are suspension feeders. At this location, introduction of species during the late eighties has not resulted in a completely new set of dominant species. Other bivalves (*M. arenaria, M. senhousia*) which likely co-dominated with *A. abdita* in the late seventies early eighties are still sometimes present in the assemblage although in reduced numbers (Fig.13).

Substrate composition: Sediment granulometry (Fig.11) was very uniform throughout the period of record. Sand is rare and usually limited to less than 5% of the mineral portion of the sediment. Fines (silt and clay) represent typically 95-100%. Percent organic content has been seasonally invariable at about 7% from 1991 to 1999, and falling to roughly 4% in the middle of 1999.

Hydrology: Delta outflow (from Dayflow) are the closest of available flow data estimates. Relationship between delta outflow and salinity at D41A are apparent.

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Water environment: Please note that water quality data in Fig. 11 was not recorded at the exact same location as the benthic sampling but comes from station D41 closer to the main channel in San Pablo Bay.
Chlorophyll a concentrations have remained mostly below 5 µg/L with very few values over µg/L. We do not see at this location a clear decline in chlorophyll concentrations after the year 1986, despite the introduction of *C.amurensis* in 1987. It is likely because large populations of filter feeders already existed at this location.
There is no long-term trend in Secchi depth at this station over the record period 1975-2004. However high flow years seem to reduce Secchi depth somewhat.
Salinity can be extremely variable at this location, ranging from 1 to 30 psu over the period 1975-2004. During low flow years it varies between 20 and 30 psu, but in high flow years like 1998 it may vary widely fro 2 to 25 psu.

Overall Summary:

Changes in substrate composition and in benthic assemblages have occurred estuary-wide in 1999-2000. These changes, however, have not been by any measure as drastic as the changes that occurred throughout the estuary in 1987-1989. No major species of organisms have been introduced in or been excluded from the benthic assemblages in recent years, and except for D28A, overall benthic abundance is not generally less than average for the study period.
With regard to the potential grazing pressure exerted by the benthos on phytoplankton (and possibly on zooplankton nauplii), the lack of biomass data forces us to remain prudent in our conclusions. However, based upon trends in the abundance of suspension feeders within the past decade we make the following remarks:

- In the San Pablo Bay shallows: Populations of suspension feeders have been higher in 2000-2004 than in 1993-1999. However, this greater abundance is mostly due to the greater abundance of the amphipod *A. abdita*, which is generally smaller in size than the bivalves whose numbers have not increased compared to the previous period (except for 2000). We also have indications that at this location suspension feeding pressure has been constantly high since 1975.
- In Grizzly Bay the bivalve population of *C. amurensis*, which had been reduced overall by high flow years over the period 1994-1999, is since 2001 back to high levels similar to those reached in 1988-1989. At this location, the invasion and subsequent dominance by *C. amurensis* has coincided with a disappearance of phytoplankton blooms.
- At the confluence, the community has remained similar to that of 1993-1999 with a loss of diversity and a shift towards species with somewhat higher salinity tolerance such as *C.amurensis* and *A. spinicorne*. Total abundance of bivalves was lower in 2001-2003 than during 1995-2000, but mostly because *C. fluminea* abundance decreased while that of *C. amurensis* increased reaching in 2004 levels similar to those it reached in 1991-1992. At this location also, the invasion by *C. amurensis* has coincided with a disappearance of phytoplankton blooms. However there is clear indication that before 1987 phtoplankton blooms did coexist with larger benthic populations comporting very high numbers of *C. fluminea*.

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- In Old River, Suspension feeder *C. fluminea*, after a moderate increase in numbers in 98-99, has declined back to the historically lower abundance level seen in 1994-1997. Although the brackish water clam *C. amurensis*, never made it to this location because it is too fresh, lower chlorophyll a levels have also become more prevalent after 1988-1989. And this despite an increase in water clarity that should have favored phytoplankton production. There are indications that before then phytoplankton production capacity might have been higher as well and that some other phenomenon than invasion by exotic bivalves might be at work in reducing chlorophyll levels.

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Figure 1

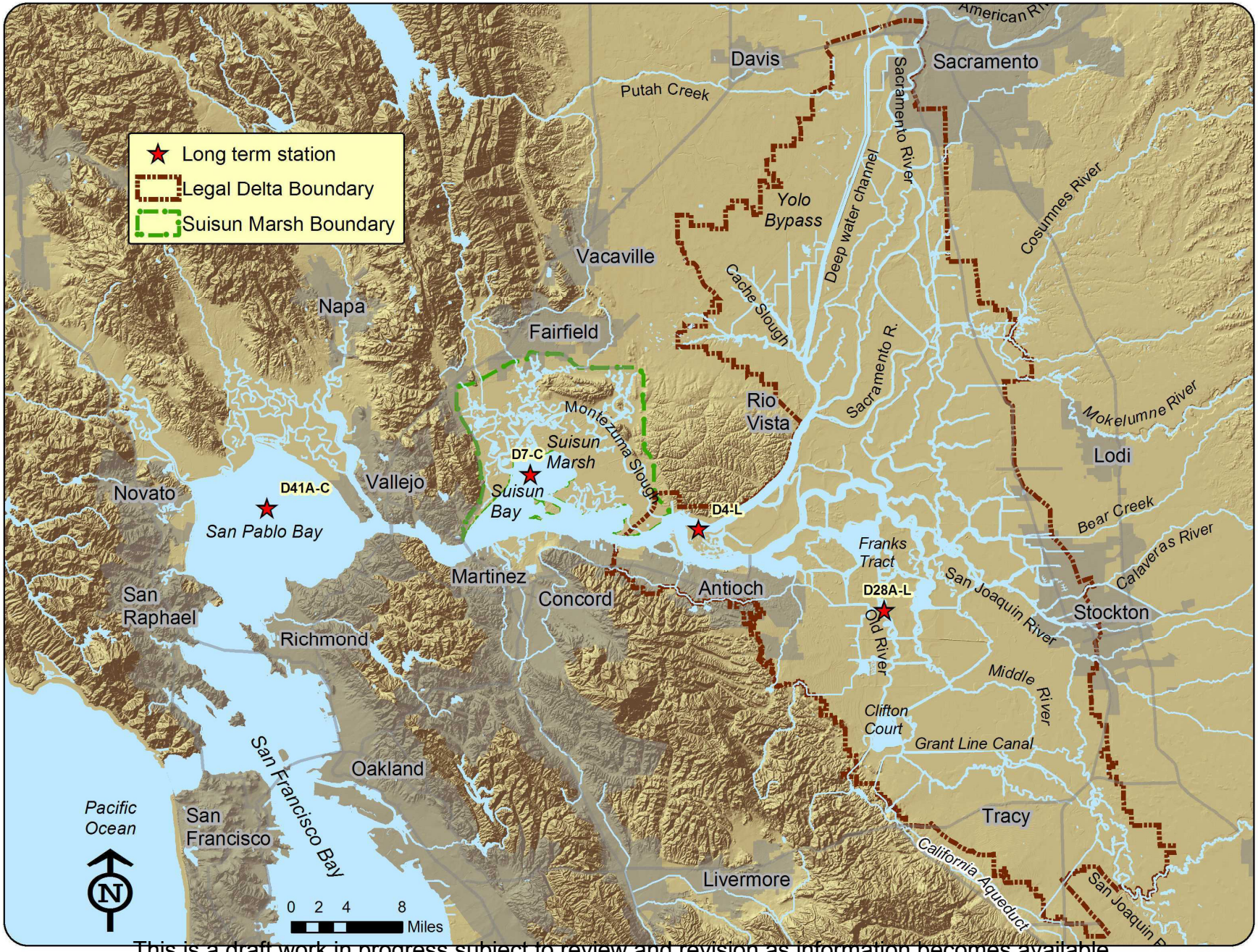

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Figure 2

Environment, Diversity and Abundance at D28A-L

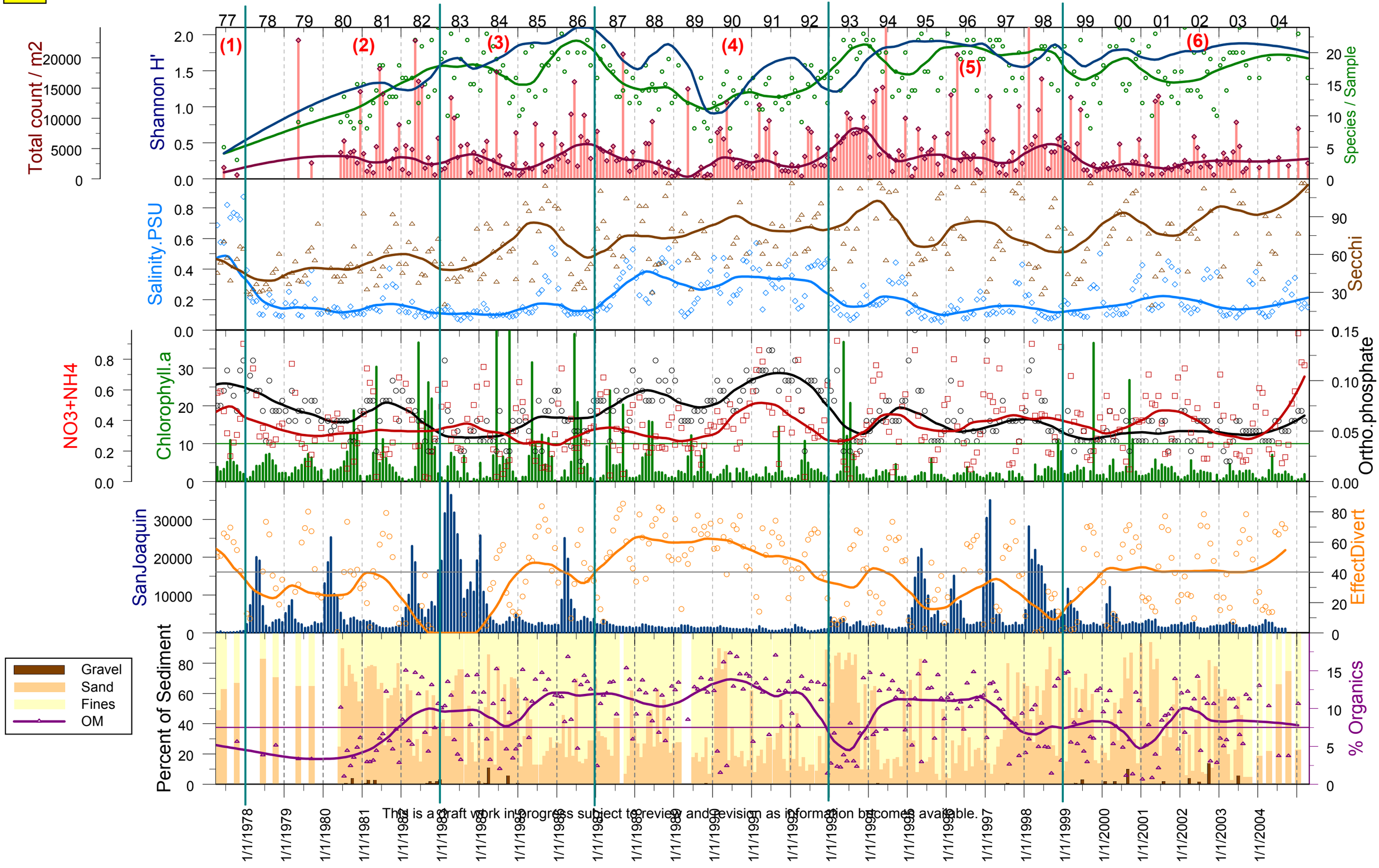

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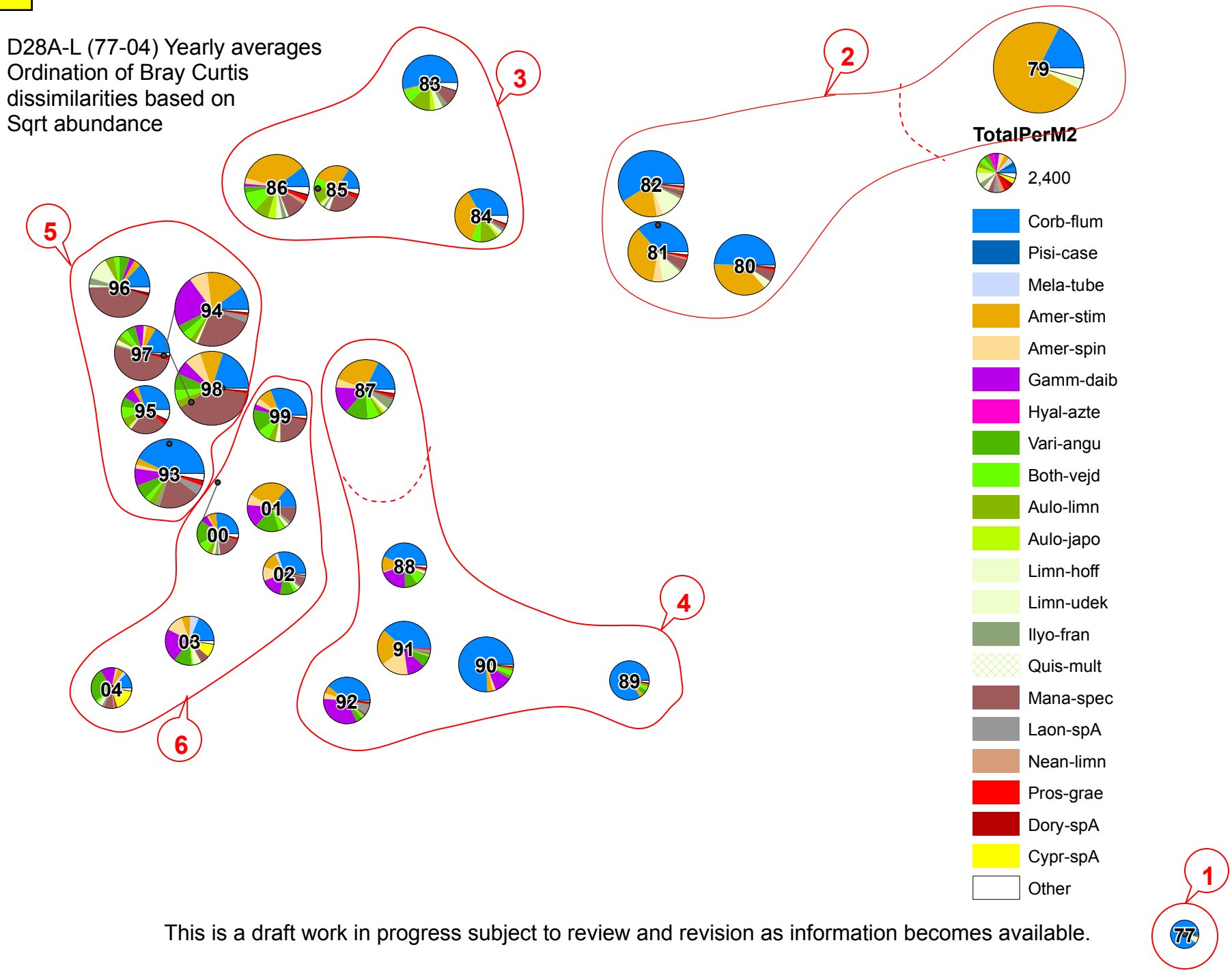
Figure 3



This is a draft work in progress subject to review and revision as information becomes available.

Figure 4

D28A-L (Old River) - Bivalves

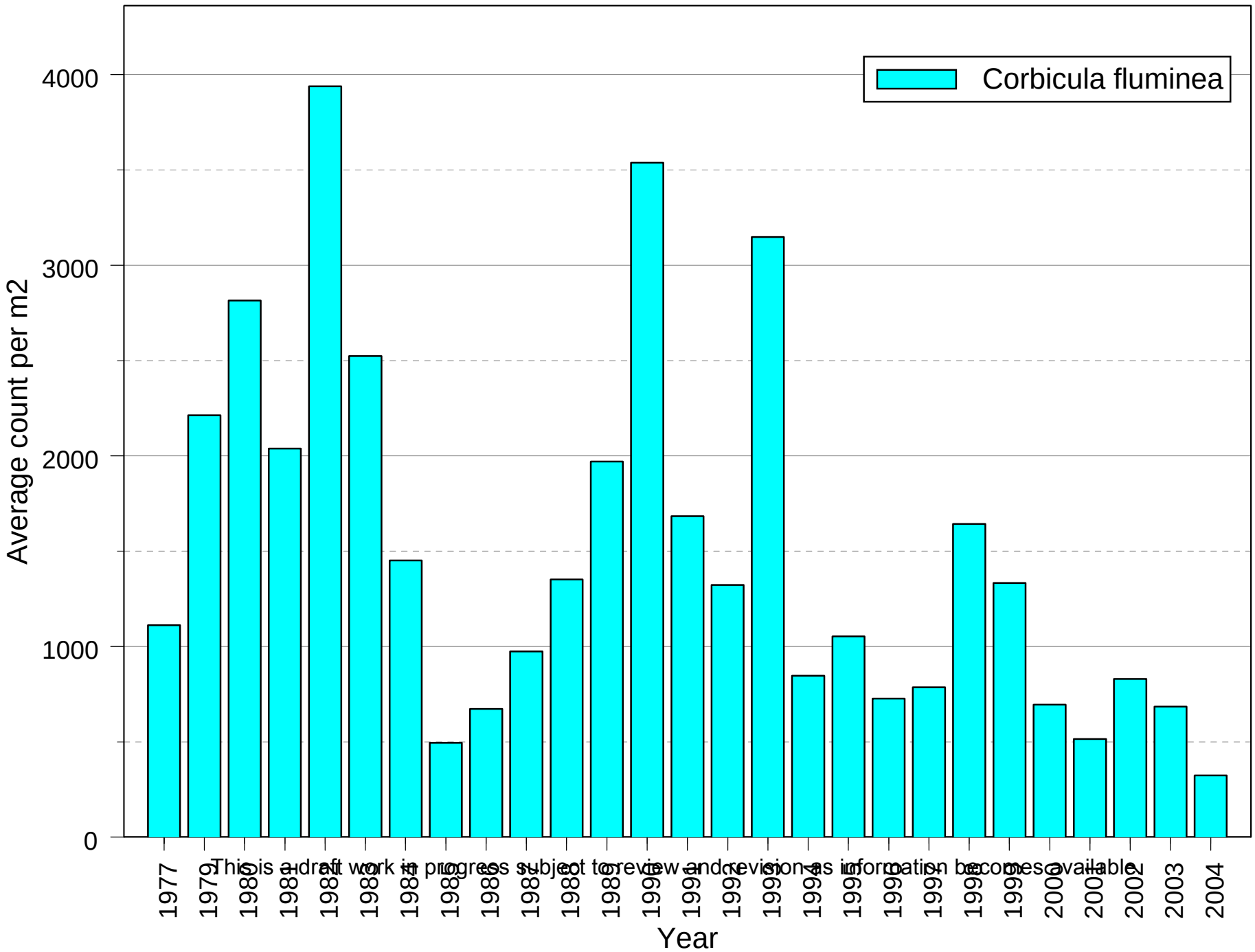


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Figure 5

Environment, Diversity and Abundance at D4-L

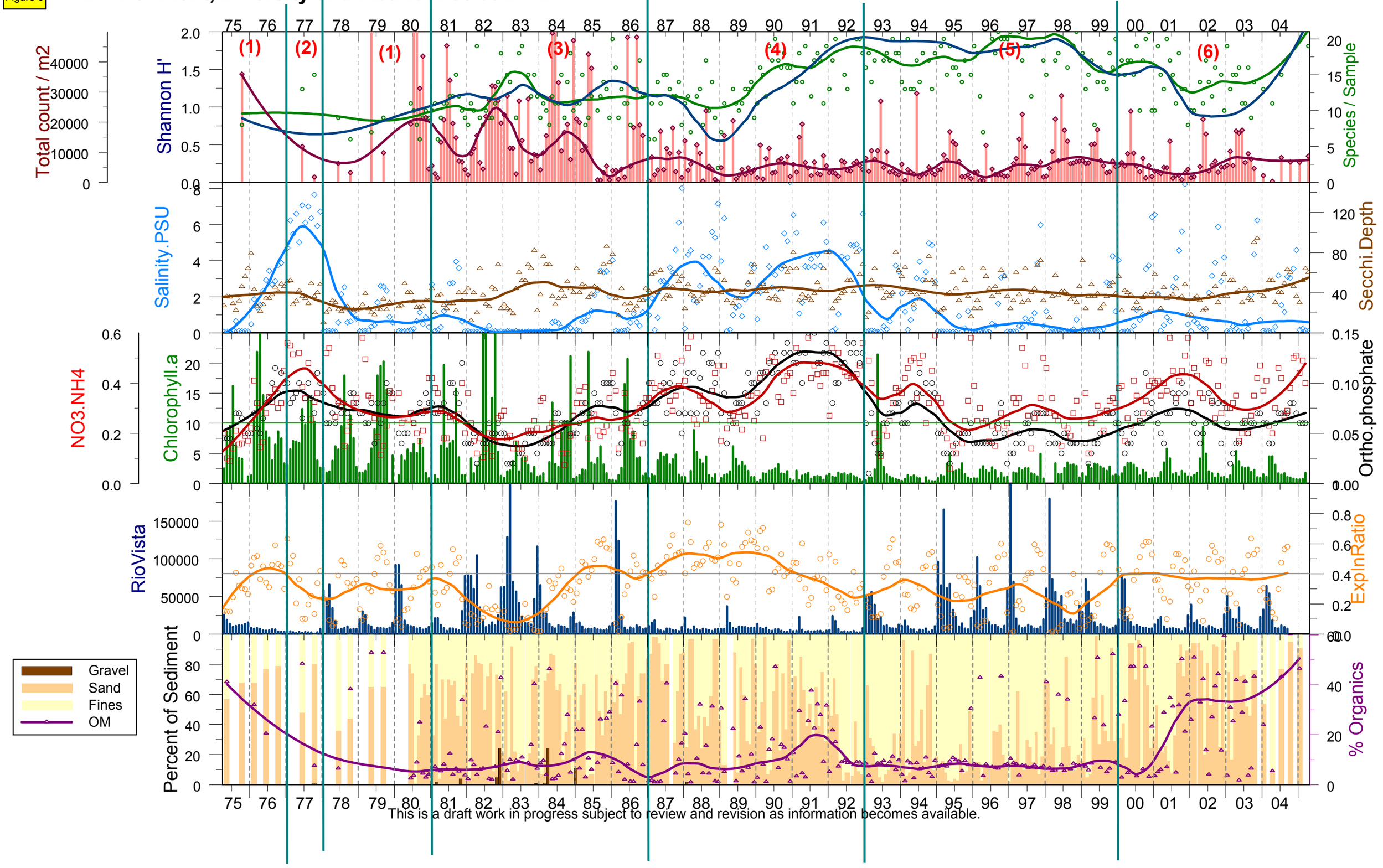

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Figure 6

D4-L (75-04) yearly averages
Ordination of Bray Curtis dissimilarities
based on Sqrt groups' abundance

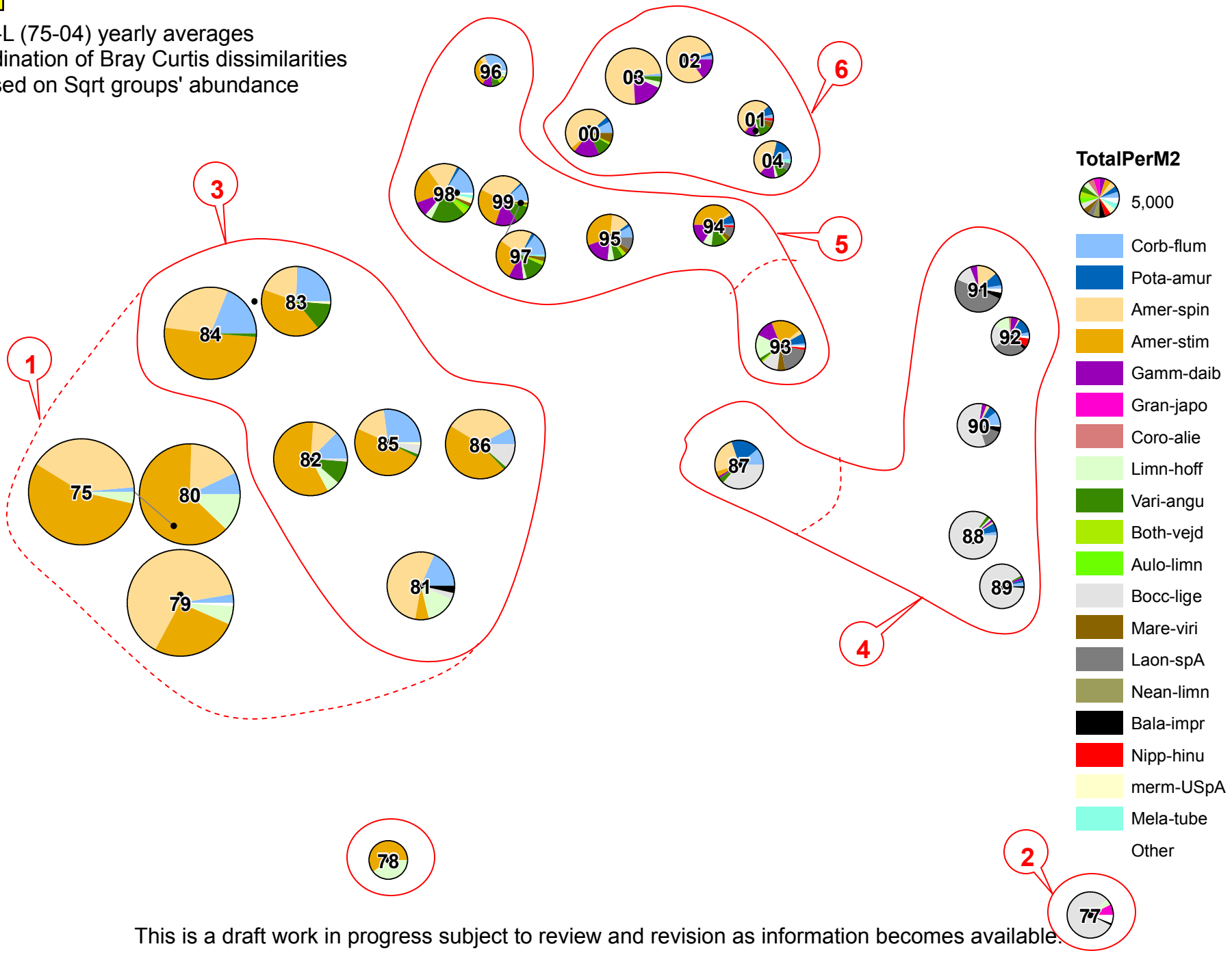

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Figure 7

D4-L (Sacramento River at confluence) - Bivalves

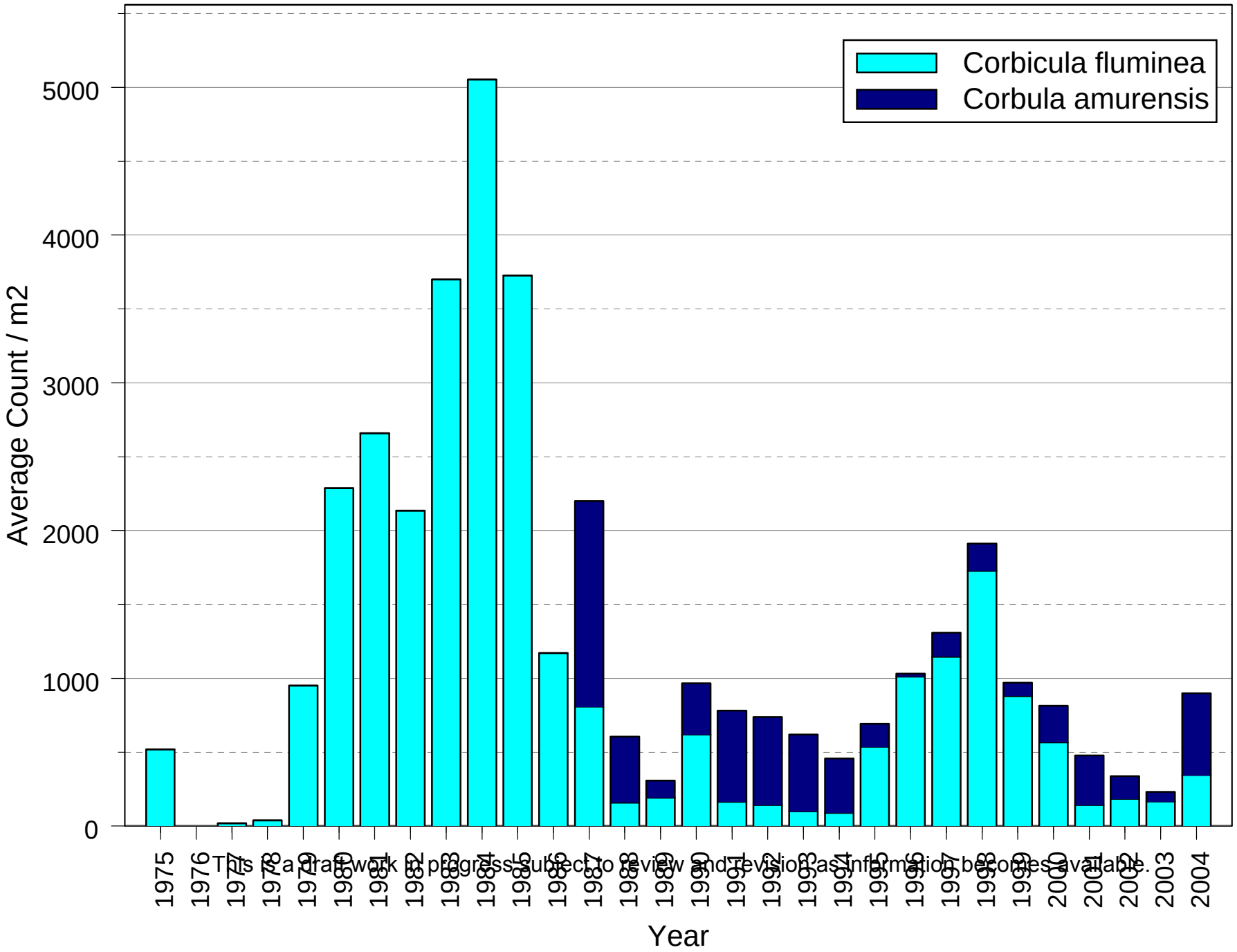

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Figure 8

Environment, Diversity and Abundance at D7

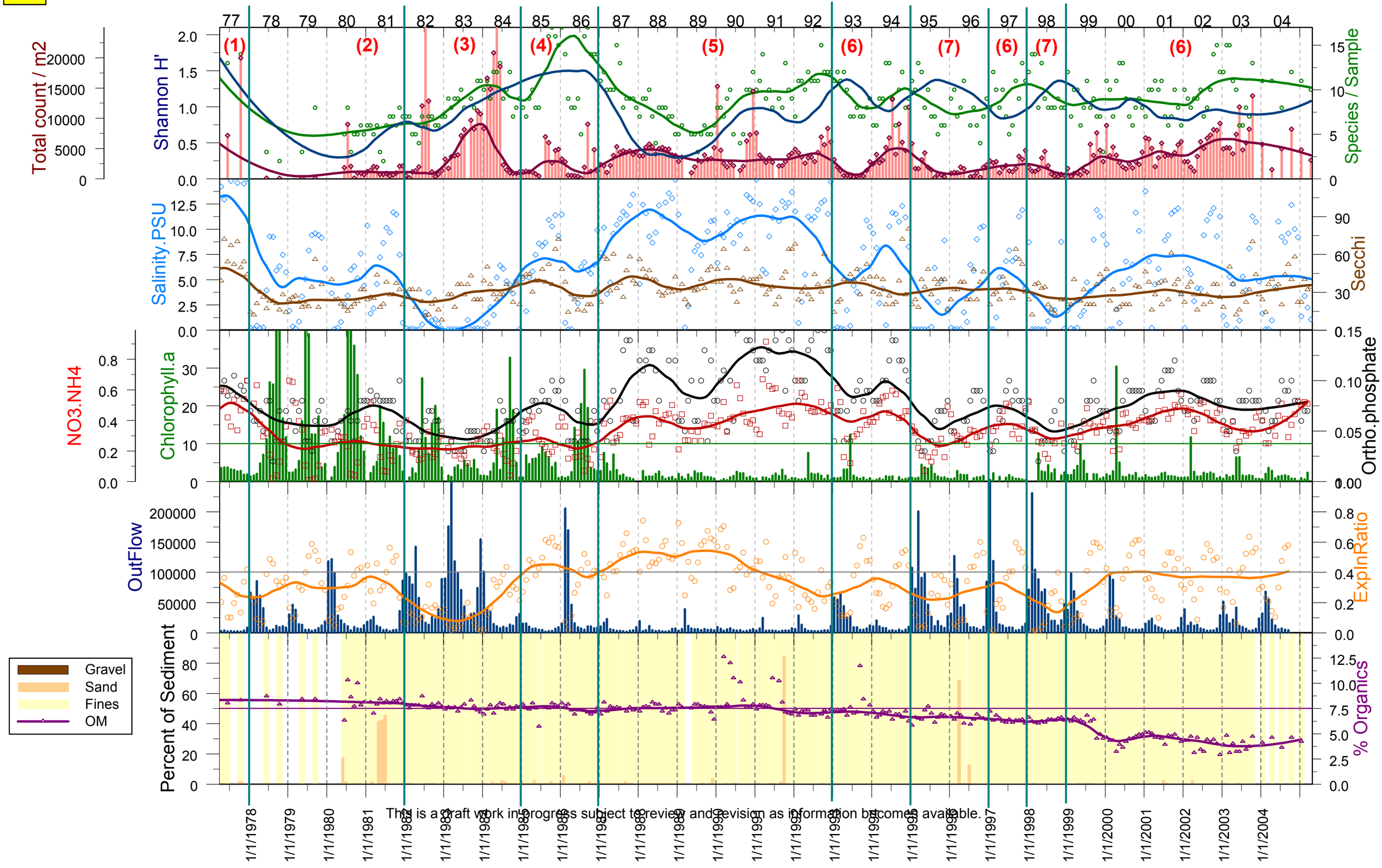

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Figure 9

D7-C (75-04) yearly averages
Ordination of Bray Curtis dissimilarities
based on Sqrt abundance

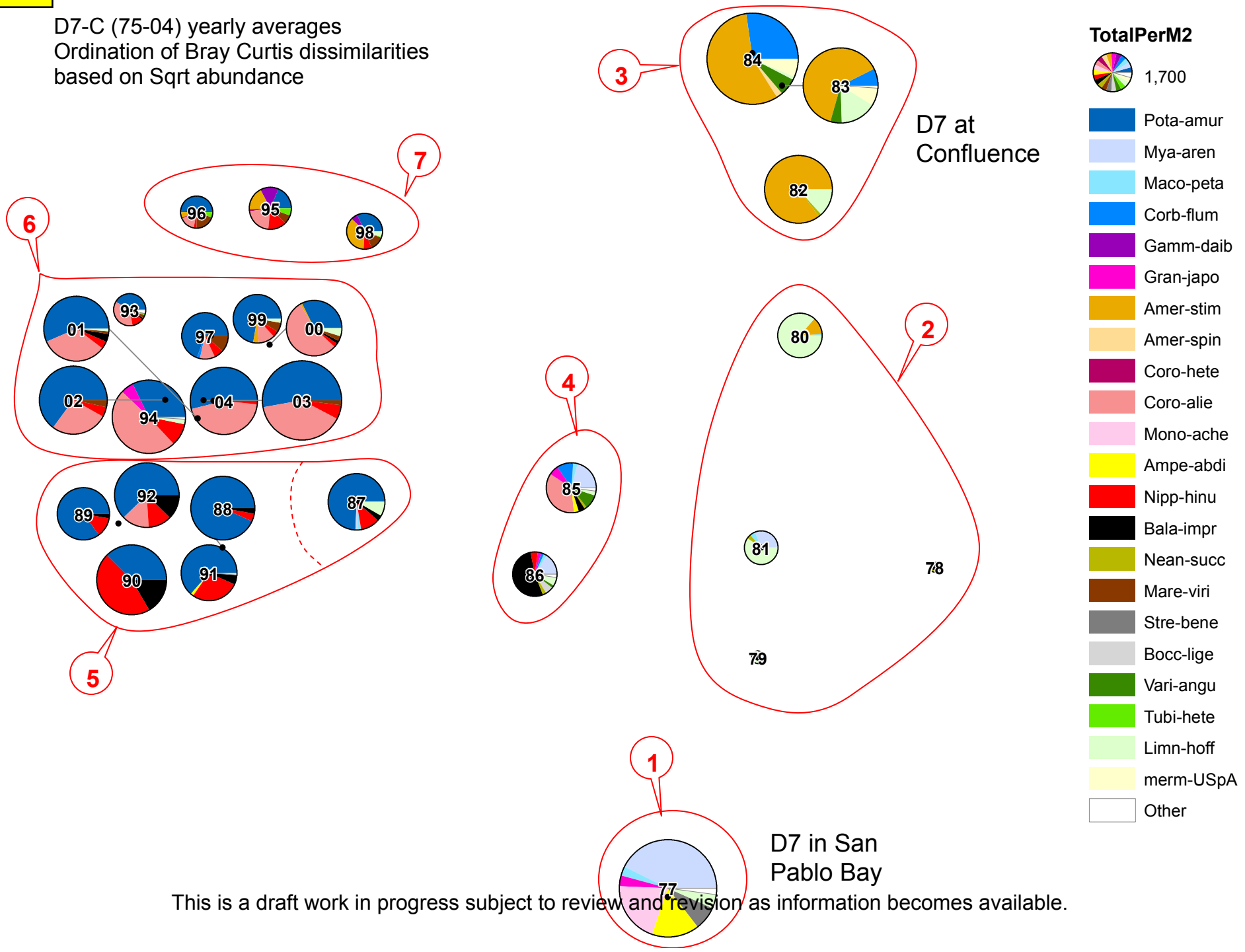

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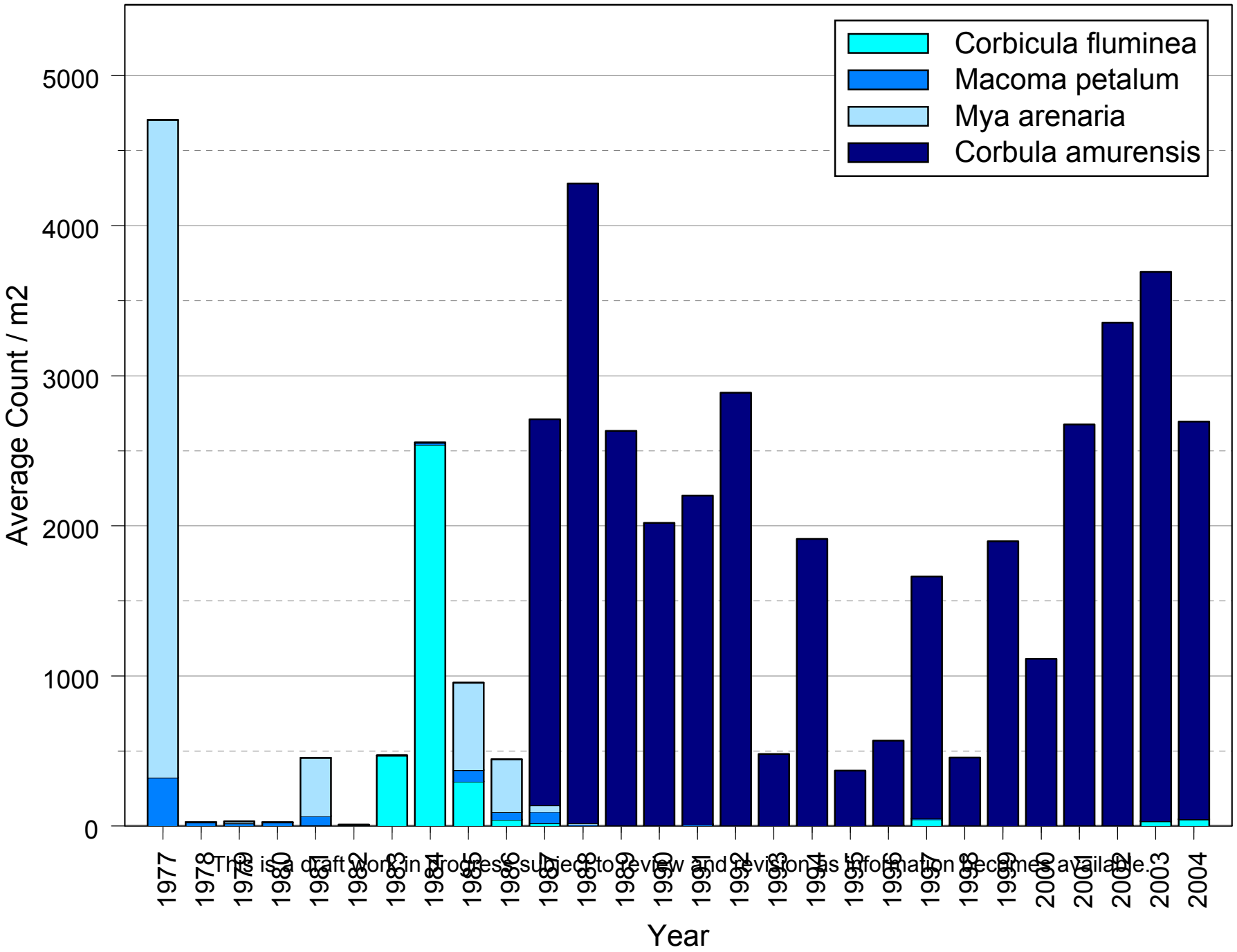
Figure 10

D7-C (Grizzly Bay) - Bivalves



This is a draft work in progress subject to review and revision as information becomes available.

Figure 11

Environment, Diversity and Abundance at D41A-C

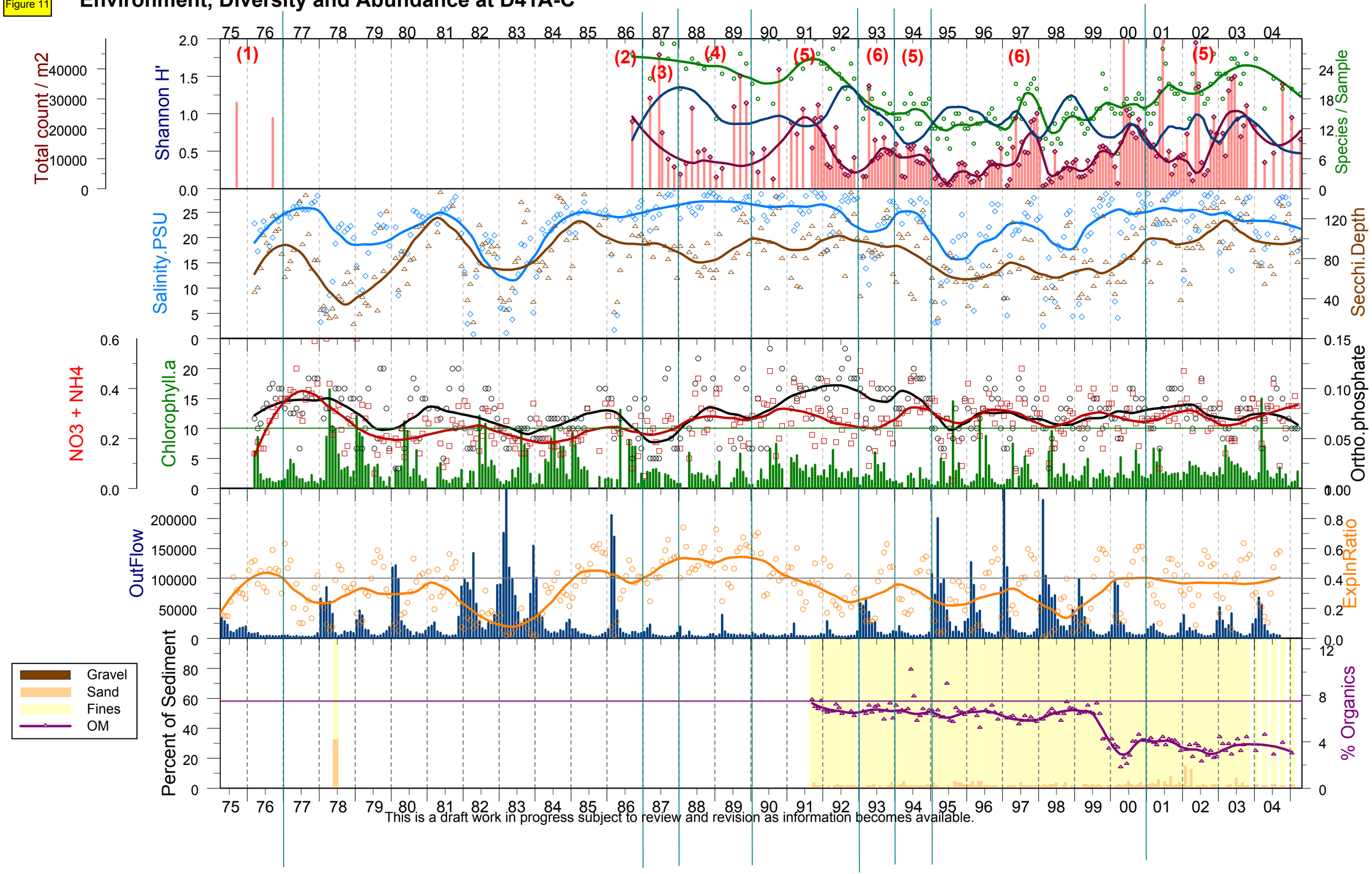
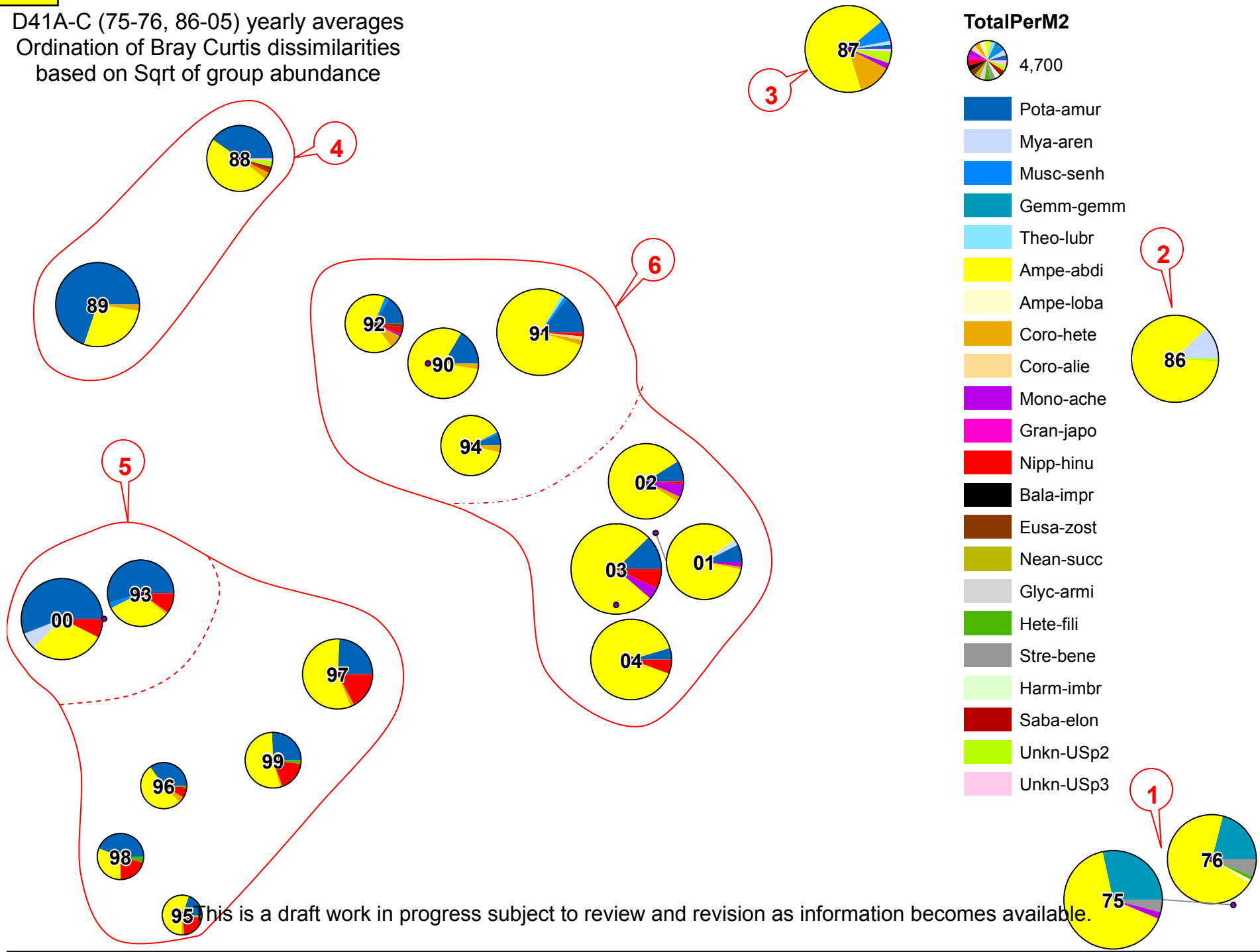
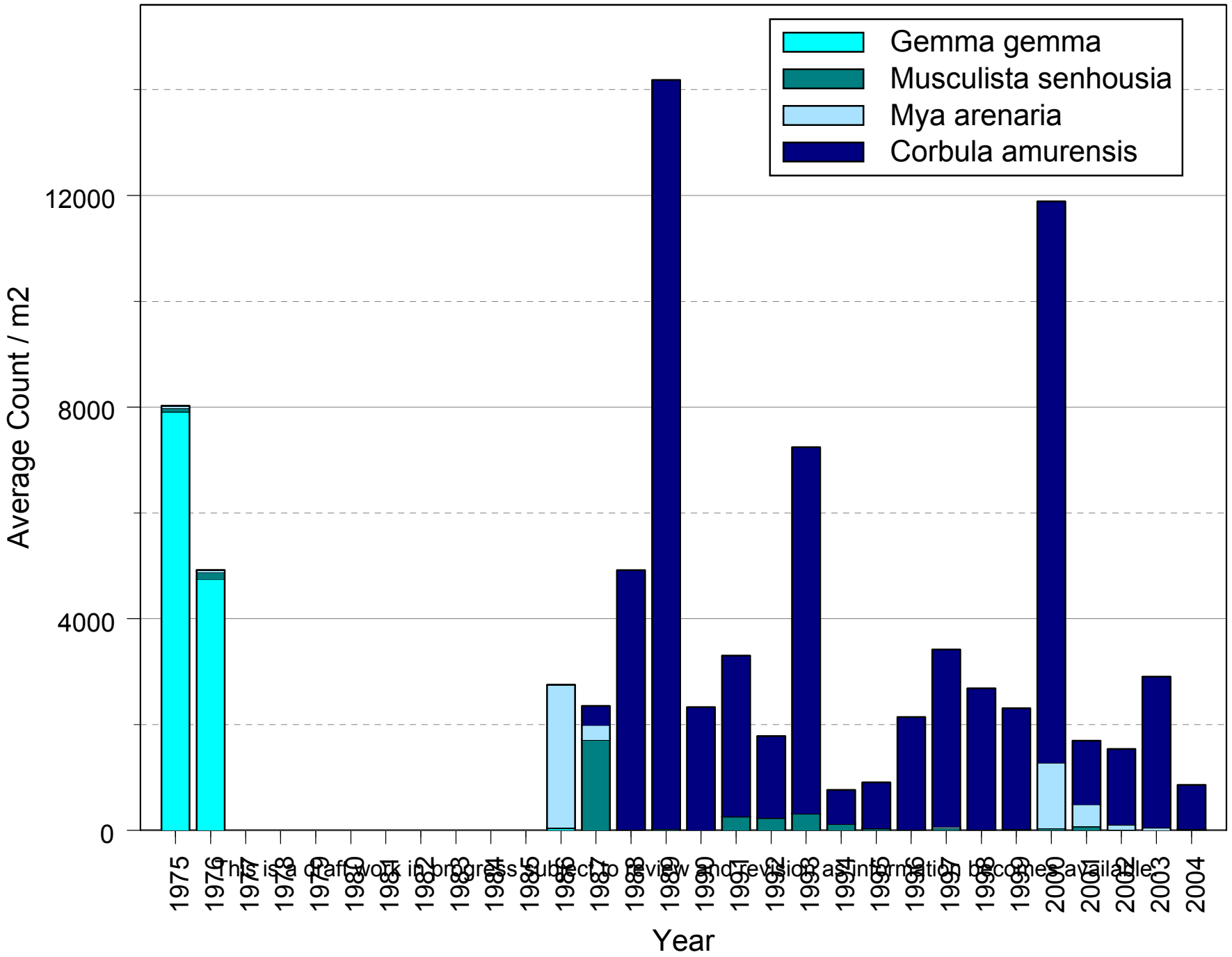


Figure 12

D41A-C (75-76, 86-05) yearly averages
Ordination of Bray Curtis dissimilarities
based on Sqrt of group abundance



This is a draft work in progress subject to review and revision as information becomes available.

Figure 13

D41A-C (San Pablo Bay shallows) - Bivalves