# Chapter II

## Shipping Patterns Associated with the Panama Canal: Effects on Biotic Exchange?

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## 1 Introduction

Shipping has been a primary mode of trade for millennia and is undergoing constant change (Couper 1972; see Suez Canal chapter). Vessel size and speed have certainly increased through time. Worldwide, the number of recipient and source ports engaged in international commerce have increased in recent history, as have the cumulative number of vessel arrivals across these ports. Together, these changes in scale and tempo of shipping are driving the increased globalization of economies.

Trade routes have also shifted through time. Changes in vessel characteristics such as motorization (speed), size, and refrigeration have overcome earlier physical or temporal constraints associated with some routes. New commodities and markets have emerged, and older ones have sometimes declined. Opening of new passages has resulted from discovery and the creation of canals. World events such as wars and trade embargos or agreements have limited use of pre-existing routes. In addition, trade routes have also responded at various timescales to environmental changes (e.g. ice cover or water level surrounding passages) and storm events.

Although it is evident that the scale, tempo, and routes of shipping are highly dynamic, the temporal and spatial pattern of changes and not been well documented to date. Many of the changes in shipping are punctuated rather than a gradual shift over time. Such shifts are exemplified by the advent of steamships or the opening of canals as new passage ways, which rapidly changed shipping on a global scale (Couper 1972, see Suez Canal chapter).

Changes in shipping patterns affect not only transport of cargo but also transfer of organisms to new geographic regions. It is well known that many species are transferred unintentionally in the cargo of ships and by the hulls and ballasted materials of ships (Visscher 1928, Carlton 1985, Carlton and Geller 1993, Coutts 1999, Gollasch 2002). Upon release to a new geographic region, many species have established self-sustaining populations. Due to the magnitude of shipping and the extensive species pool associated with ships' ballast and hulls, shipping is a leading source of biological invasions in coastal ecosystems throughout the world (Cohen and Carlton 1995, Reise 1998, Ruiz et al. 2000, Fofonoff et al. 2003, Hewitt et al. 2004).

In this chapter, we begin to explore some patterns of shipping associated with the Panama Canal (see Cohen, Panama Canal chapter I for history and description of the canal). The opening of this passage in 1914 was indeed a punctuated event, causing a change in commercial shipping on a global scale. We compiled historical records from the Panama Canal Authority to (a) describe changes in the magnitude of shipping through the Panama Canal from 1914-2004, (b) examine the directional flux of different vessel types, including the frequency of ballasted versus cargo laden transits, through the canal and (c) compare the magnitude of shipping through the canal to that of the largest port systems in the United States. Based upon this background, we consider the implications of creating this new passageway, and its expanding use, for biological invasions.

## 2 Magnitude and tempo of commercial shipping in the Panama Canal

Since its opening in 1914, an estimated 781,363 ocean-going commercial vessels have passed through the Panama Canal. This estimate excludes all ships (a) operated by Panama and Colombia, (b) operated by the United States through 2000, or (c) under 500 tons displacement.

The number of transits by these ocean-going vessels shows a strong increase through time, exhibiting two periods of rapid increase followed by relatively little inter-annual change (Figure 1A). The first period of increase occurred from 1915 (1,075 transits) to 1928 (6,456 transits), where the number of annual transits are reported by fiscal year ending in June. The number of annual transits did not exceed this range until 1952. There was a marked decline in traffic during World War II (1942-1945), when the number of transits ranged from 1,562 to 2,688. The second period of increase occurred from 1952 (6,562 transits) to 1971 (14,020 transits). Since this time, annual transits have remained relatively stable, having a mean of 12,625 transits (sd = 1,030) and a range of 9,936 to 15,194.

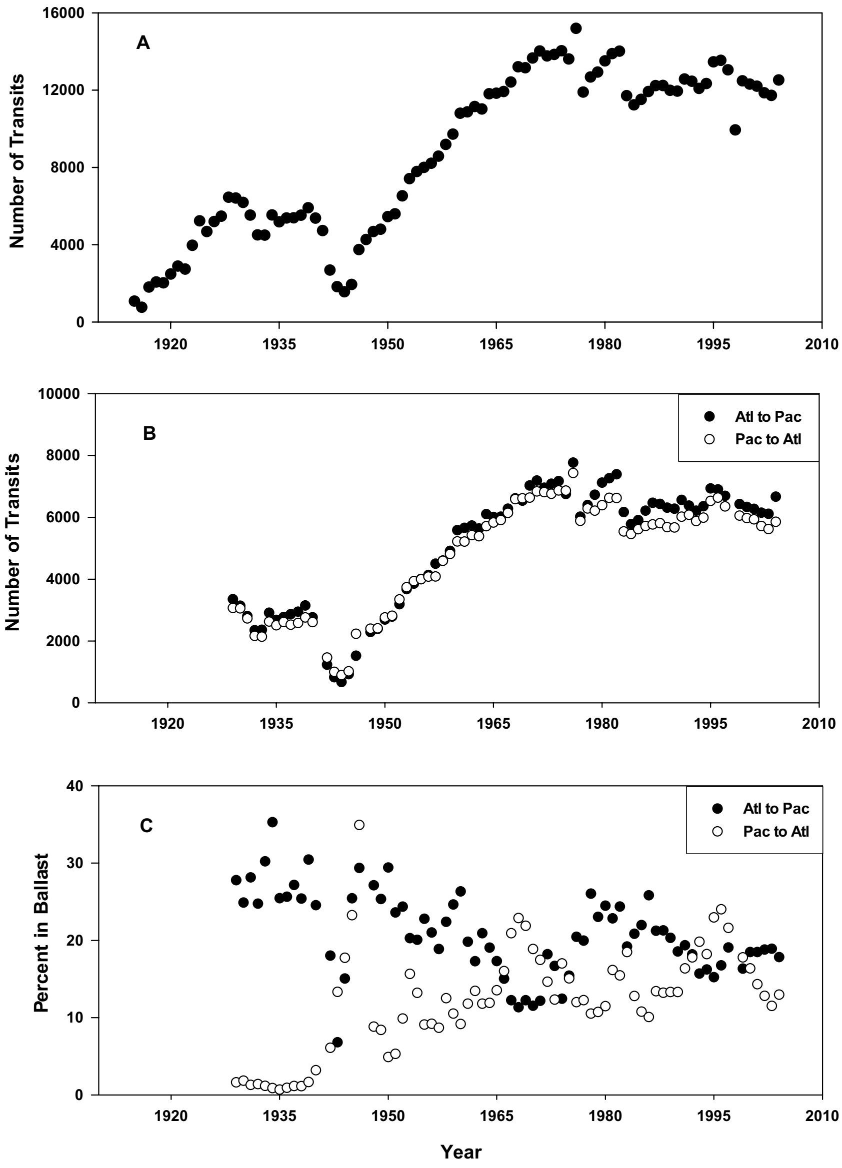


*Fig. 1.* Number of transits by year. Shown for each year is the number of transits through the Panama Canal by ocean-going commercial vessels. (A) Total number of transits, (B) Number of westbound transits (dark circles) and eastbound transits (open circles), and (C) Percent of westbound and eastbound transits reported to be ballasted. Data as reported by the Panama Canal Authority for each fiscal year (ending in June).

In recent years, small commercial vessels (<500 tons) added approximately 10% more transits. For example, the number of reported annual transits for small vessels ranged from 1,323 to 1,517 for the years 2002 - 2004. Today, we therefore estimate total commercial traffic from ocean-going and small vessels to be approximately 13,000 to 14,000 transits per year. This is the current scope of international traffic using the canal, as these estimates exclude domestic (local) traffic and also recreational vessels.

## 3 Overall direction of traffic and ballasted transits

Beginning in 1929, data were available on the annual number of transits in each direction and whether these ships were laden with cargo versus in ballast. As might be expected, the number of transits in each direction is similar among years (Figure 1B).

*Table 1.* Cumulative statistics for total and ballasted transits by direction. Summary statistics are shown for two different time periods: (A) 1929 - 2004; (B) 1929 - 1991.

| | Atlantic to Pacific | Pacific to Atlantic |
|---|---|---|
| A. 1929 - 2004 | | |
| **Total Transits** | **366,693** | **348,914** |
| % of Total Transits | 51.20% | 48.80% |
| **Total Transits in Ballast** | **72,979** | **47,271** |
| % of Total Transits in Ballast | 60.70% | 39.30% |
| % of Directional Transits in Ballast | 19.90% | 13.50% |
| B. 1929-1991 | | |
| **Total Transits** | **289,286** | **276,325** |
| % of Total Transits | 51.10% | 48.90% |
| **Total Transits in Ballast** | **59,450** | **34,432** |
| % of Total Transits in Ballast | 63.30% | 36.70% |
| % of Directional Transits in Ballast | 20.60% | 12.50% |

However, there appears to be a strong directional bias in the percentage of transits in ballast (Figure 1C). Such directional data were available for the 73 of 76 years from 1929-2004, as shown in Figure 1C. For 56 (77%) of these years, the percentage of transits in ballast from Atlantic to Pacific exceeded those in the opposite direction, often by a large margin. Interestingly, the difference in annual percentage of ballasted eastbound versus westbound voyages was greatest before 1965, suggesting temporal change and convergence in directional ballast operations through time.

These patterns are equally evident when comparing cumulative data across all years (Table 1A). From 1929-2004, 51.2% of all transits were westbound (Atlantic to Pacific) and 48.8% were eastbound (Pacific to Atlantic). During this same period, the westward traffic accounted for 60.7% of all ballasted voyages for both directions. Since the cumulative number of transits was similar in each direction, this indicates that a higher percentage of westbound traffic was in ballast (19.9%) compared to eastbound traffic (13.5%), as shown in Table 1A.

## 4 Direction of traffic and ballasted transits by vessel type

To gain a better understanding of directional patterns of ballasted transits, we examined the frequency of transits classified as “in ballast” by vessel type and direction from 1929-1991. During this time period (1929-1991), new types of vessels were added to the classification scheme used by the Panama Canal Authority, probably reflecting changes in specialization, design, and size of vessels (Couper 1972). General Cargo and Tanker vessels were present in the classification scheme for the entire period, whereas other vessel types were represented for only part of the period (Ore Carriers 1938-1972; Dry Bulk 1968-1991; Refrigerated Cargo 1968-1991; Containers 1968-1991; Passenger vessels were not consistently reported until 1938-1991). It is likely that some of these latter vessel types are included earlier as General Cargo vessels and were not classified separately until they began to increase in frequency, but any lag-time in reporting new vessel types in the transit records has not yet been evaluated. After 1991, the number of different commercial vessel types included in the classification scheme for transits in the Panama Canal doubled, expanding from seven to over fourteen. To simplify our analysis, and to avoid the confounding effects of adding additional vessel types through time, we examined transits for the 62-year period prior to 1992.

For the period 1929-1991, most (63.3%) of all ballasted transits occurred from the Atlantic to Pacific (Table 1B) and a higher percentage of westbound transits (20.6%) were ballasted than eastbound transits (12.5%). A similar directional bias exists in ballasted transits for the period 1929-2004 (Table 1A), but this pattern is weighted strongly by the early years and changed dramatically through time (as noted above and seen in Figure 1C); the cause of such temporal change is the focus of current study.

Figure 2A shows the composition by vessel type for all transits from 1929-1991. General cargo vessels were the most frequent vessel type (50% of total), followed by dry bulk carriers (15%), tankers (14%), refrigerated cargo vessels (8%), containerships (5%), ore carriers (1%), and passenger vessels (1%). Other vessel types in combination contributed the remaining 6%, and included military vessels, but little information was available to characterize these further.

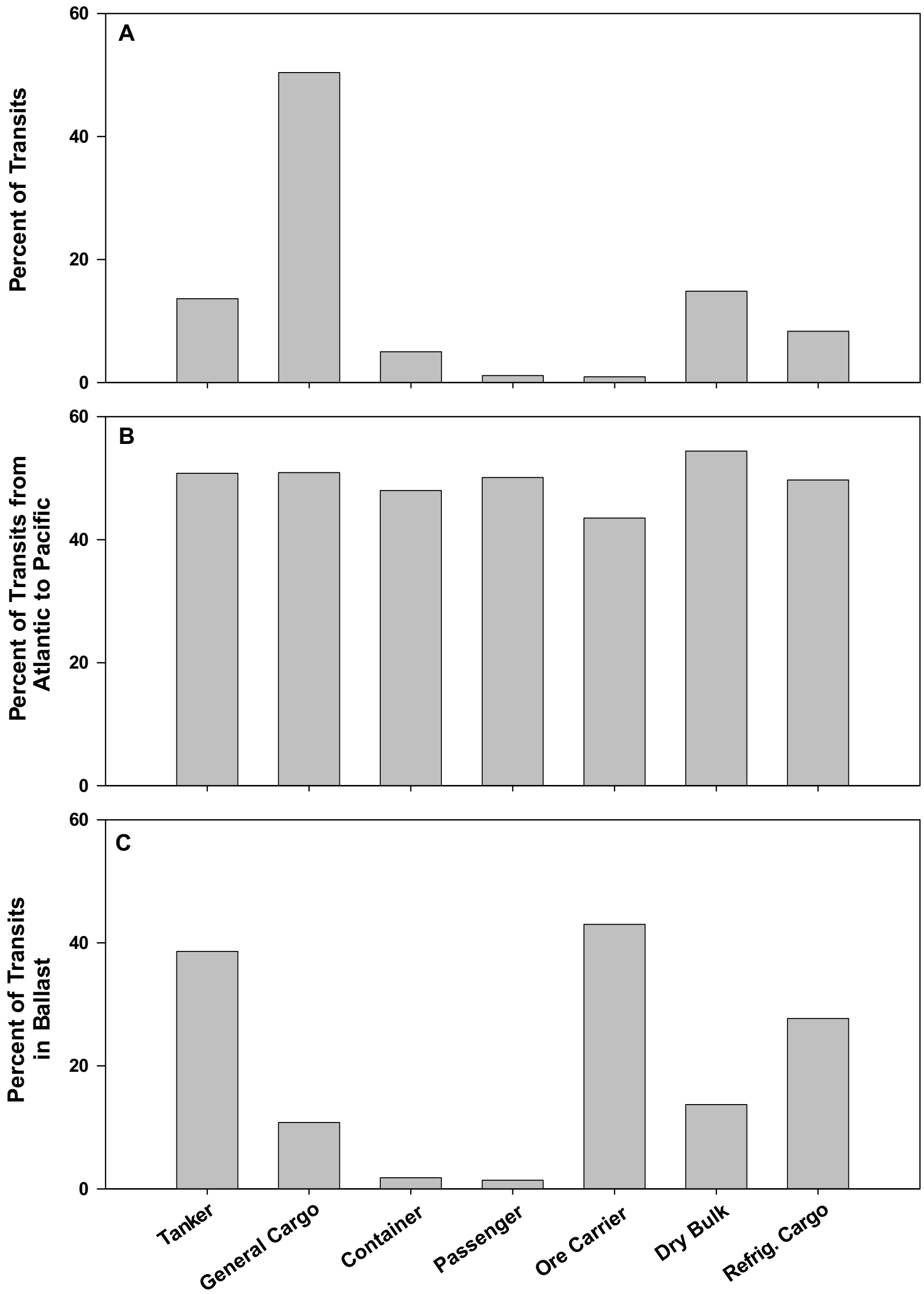


*Fig. 2.* Cumulative transit statistics by vessel type, 1929 - 1991. Shown are (A) percent of total transits by vessel type, (B) percent of transits within vessel type that was westbound, Atlantic to Pacific, and (C) percent of transits within each vessel type that was ballasted.

In general, the flux of vessels eastbound was equivalent to that westbound for each vessel type. As shown in Figure 2B, the percentage of total traffic that was westbound (Atlantic to Pacific) ranged from a low of 43.5% (for ore carriers) to a high of 50.9% (for general cargo vessels).

Five of the seven vessel types were classified as having arrived to the Panama Canal "in ballast" for at least 10% of their total transits (Figure 2C). Ore Carriers, tankers, and refrigerated cargo vessels arrived most frequently in ballast (43%, 38%, and 27% of transits, respectively). Dry bulk and general cargo vessels arrived in ballast much less frequently (14% and 10% of transits). Less than 2% of container and passenger vessels arrived in ballast.

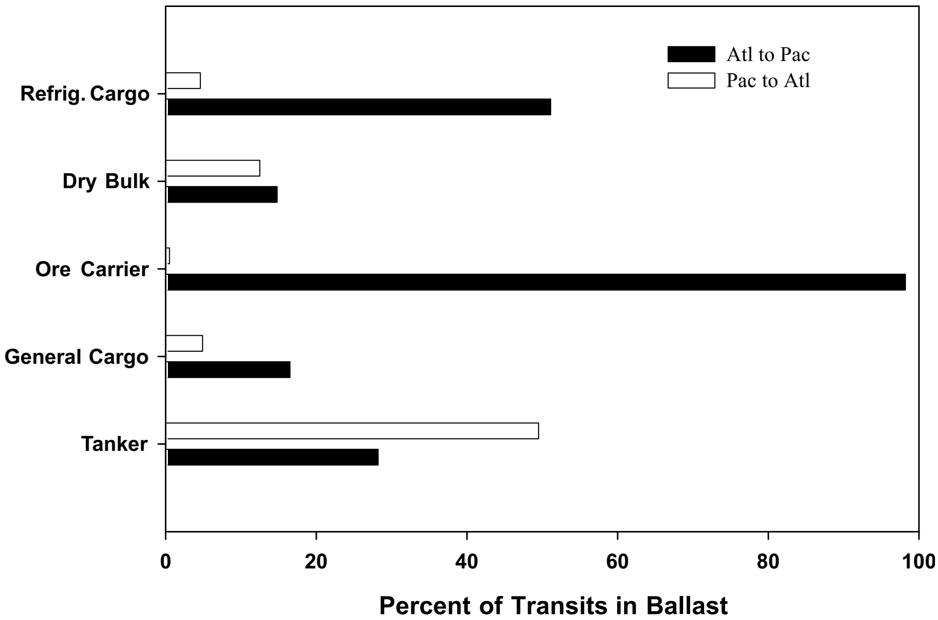


*Fig. 3.* Percent of ballasted transits by vessel type and direction, 1929 - 1991. Shown separately for each vessel type is the percent of eastbound and westbound transits in ballast.

For these five vessel types most often arriving in ballast, Figure 3 contrasts the percent of ballasted transits for eastbound versus westbound traffic. For four of the five vessel types, a higher percentage of in ballast transits occurred in the westbound direction. This was most pronounced for ore carriers and refrigerated cargo vessels. Nearly all ore carriers were reported in ballast from the Atlantic to Pacific (98%) and almost none (2%) were classified in ballast when eastbound, suggesting transport of cargo in only the latter direction.

Approximately 51% of westbound refrigerated cargo vessels were in ballast compared to 5% of eastbound transits by this vessel type.

Although much less pronounced, the percentage of cargo vessels in ballast was still 3-fold greater in the westbound versus eastbound direction. The percentage of dry bulk carriers in ballast was very similar for eastbound (12.5%) and westbound transits (14.8%). In contrast, tankers exhibited a bias in the opposite direction for this time period. The percentage of vessels in ballast for eastbound transits was approximately twice that reported for westbound transits.

Such directional bias may have important consequences for species transfers and biological invasions. In general, ships laden with cargo can carry much less ballast water than those considered in ballast. For this reason, the frequency of ballasted voyages may provide a useful, albeit coarse, proxy for the net direction of transfer for biota associated with ballast tanks within particular vessel types.

At the present time, we are not able to go beyond this coarse-level analysis and estimate actual volumes of ballast water transferred through the Panama Canal or compare these volumes across vessel types, source regions, and recipient regions. The frequency distribution and average for ballast water volumes carried by any one vessel type (e.g. tankers) when 'in ballast' will certainly differ from the others (Carlton et al. 1995, Verling et al. 2005). Even within vessel type, there are also likely to be differences through time that result from changes in vessel size, design, and cargo. While it is evident that many factors influence ballast water use (volume) by ships, and that this affects transfer and dynamics of associated biota, the specific details surrounding ships in the Panama Canal remain unresolved (see also Effects of the Panama Canal on Biotic Exchange).

## 5 Relative scale of shipping associated with the Panama Canal

It is important to consider the current scale and nature of shipping in the Panama Canal in the context of other major port systems, underscoring the broad-scale shift in commercial shipping patterns that resulted from opening of this passageway. For this purpose, we compare the number of transits in the Panama Canal to commercial ship arrivals to ports of the United States at the present time.

From 2000-2004, the mean number of annual transits in the Panama Canal by commercial vessels was 12,121 (sd = 325). All of these are commercial vessels arriving from outside the country, as transits from Panama and Colombia are excluded from these estimates. Most of these vessels are not undergoing any cargo operations and pass through the canal as quickly as possible, with a transit time of 6-12 hours. The last port and next port of call of these vessels, defining the trade routes through the canal, is the topic of ongoing investigation.

For this same time period, all ports in the United States received approximately 100,000 ship visits per year (U.S. Maritime Administration, unpublished data). While this surpasses the number of transits in the Panama Canal, these arrivals are distributed across scores of ports and thousands of miles, along both the Atlantic and Pacific coasts. A more direct comparison to the Panama Canal, where ships pass the same geographic location, would be to consider individual port systems in the U.S. Each of the largest port systems in the U.S. received annually less that 50% of the total transits in the Panama Canal for the same years, 2000-2004 (Figure 4). The mean number of annual arrivals to each of the six largest U.S. port systems ranged from 2,118 to 5,358.

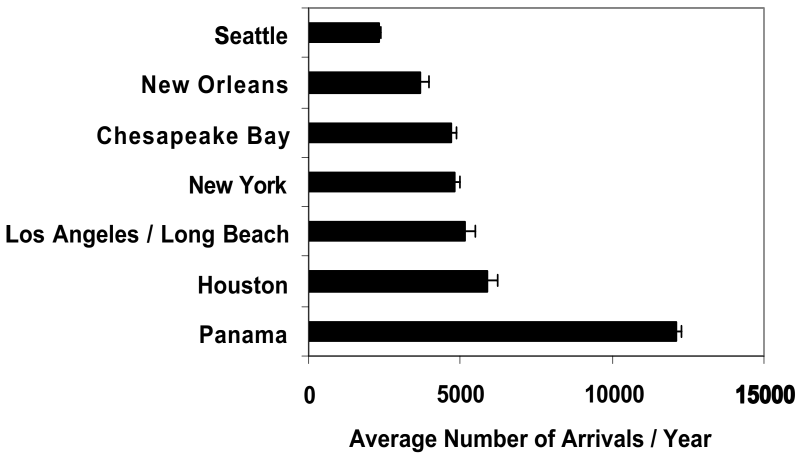


*Fig. 4.* Mean number of annual arrivals by location, 2000 - 2004. Shown is the mean number (+ s.e.) of arrivals to each of six major port systems in the United States compared to mean number (+ s.e.) of total transits for the Panama Canal.

It is also noteworthy that the number of arrivals to U.S. ports included both foreign and domestic (coastwise) traffic, whereas those reported for the Panama Canal are only foreign arrivals. Approximately 50% of arrivals to the U.S. ports are domestic in origin, and domestic arrivals to the six U.S. ports in Figure 4 ranged from 23-79% of the total.

## 6 Effects of the Panama Canal on biotic exchange

The creation of the Panama Canal as a major passageway for commercial shipping, where none existed previously, has affected the movement of aquatic organisms in two general ways: (1) unaided movement of organisms into or through the canal from adjacent waters and (2) transfers of organisms by ships. Either mode of biotic exchange can breach historical barriers to dispersal and result in biological invasions, allowing organisms to establish self-sustaining populations in new geographic locations.

For unaided dispersal of organisms via the canal, especially coast-to-coast movement across Panama, a great deal depends upon the organisms' environmental tolerance. Cohen (Panama Canal chapter III) reviews examples of several fish and invertebrate taxa that appear capable of making the transit through the canal. However, the transition from marine to freshwater may be very restrictive, creating a dispersal barrier for many species (Rubinoff 1970). Certainly some species may raft (Sheffey 1968, Thiel and Gutow 2005), possibly avoiding full and prolonged exposure to freshwater by attaching to floating materials. Others may be have environmentally tolerant resting stages (e.g. seeds, eggs, and cysts) or be associated with fast-moving organisms, perhaps as commensals or parasites, facilitating survivorship and transport. The capacity for dispersal unaided by ships, including especially salinity tolerance and the extent of rafting, remains largely to be studied in the Panama Canal system (Rubinoff 1970).

With respect to ship-mediated dispersal, it appears that a massive movement movement of organisms has occurred via ships using the Panama Canal. For almost a century, the canal has operated as a focal point for international ship traffic, shaping trade routes on a global scale. Approximately 800,000 commercial ship transits have now occurred, having many potential implications for the ship-mediated transfer of organisms in a regional and global context. However, to a large extent, we can only draw inferences (outlined below) about the transfer of organisms by these ships, and these await further data for testing.

### 6.1 Ship-mediated transfer: Regional perspective

In general, the coasts of Panama and surrounding region have been exposed to an increased propagule supply of non-native organisms, resulting from the large and continuous flux of transiting ships. These ships arrive from many parts of the world, and they would not otherwise have come to this region except for the canal. There exists a vast body of research from around the world describing abundant and taxonomically diverse assemblages of organisms that are transported in and on ships (see below). As a result, it *is* certain that ships arriving to the canal transport organisms and that some of these organisms are released to surrounding waters (Rubinoff 1970, Dawson 1973; see also Cohen, Panama Canal chapter III for discussion).

Ship-mediated transfer of aquatic organisms occurs primarily through association with ships' ballasted materials and ships' hulls. Organisms are routinely entrained in ships' ballast tanks, which are filled with surrounding waters at one port or location (to maintain stability, under rough conditions or often in lieu of cargo) and discharged at subsequent ports of call (Carlton 1985, Carlton and Geller 1993). Nearly all ballast tanks contain living organisms. It is not unusual to find concentrations of organisms in the water itself in the range of $10^0$ - $10^2$ zooplankton per liter, $10^3$ - $10^6$ phytoplankton per liter, $10^8$ - $10^9$ bacteria per liter, and $10^9$ - $10^{10}$ viruses per liter (Smith et al. 1999, Zhang and Dickman 1999, Drake et al. 2001, Minton et al. 2005). Organisms also reside at the bottom of ballast tanks, and microorganisms form biofilms on the inner surfaces of these tanks (Bailey et al. 2005, Drake et al. 2005). Moreover, organisms associated with tank bottoms and surfaces can form resting stages or cysts that can remain viable for relatively long periods of time, even with little overlying water (Bailey et al. 2003). Thus, when ballast is discharged, organisms are released to the surrounding waters.

Organisms are also frequently found on the exposed, underwater surfaces of ships. Contemporary with the operation of the canal, a wide variety of species have been reported from around the world on the hulls, rudders, and other underwater surfaces (Visscher 1928, Coutts 1999, Gollasch 2002, Minchin & Gollasch 2003). Organisms also appear to be common in the sea chests of ships; although part of ballast intake systems, these are protected recesses along the outer surface and therefore easily colonized by a diverse array of organisms (Coutts et al. 2003).

Based upon existing information across many ship types and global regions, we surmise that (a) most ships arriving to the Panama Canal have living aquatic organisms in their ballast tanks and outer surfaces, (b) the cumulative number of these organisms passing through the region through time must be great, and (c) viable organisms (propagules) have frequently been released from the ballast tanks and hulls of vessels to local waters. Given the importance of ship-mediated transfers as a source for biological invasions in many parts of the world (Cohen and Carlton 1995, Ruiz et al. 2000, Hewitt et al. 2004), we might also expect many non-native species to be established along the coasts of

Panama due to shipping. However, there is a paucity of data available to characterize the quantity and species diversity of biota associated with arriving vessels to Panama or the extent to which propagules are released to the surrounding waters (see discussions by Rubinoff 1970 and Cohen, Panama Canal, chapter III). The capacity of such organisms to tolerate and colonize local waters, or the extent to which invasions have already occurred, also has not been adequately tested, despite some earlier surveys (see Panama Canal chapter III for review). Thus, a robust assessment of the relationship of shipping to propagule delivery and invasion dynamics in the region is not yet available.

## 6.2 Ship-mediated transfer: Global perspective

In addition to any regional effects on biotic exchange, the Panama Canal has also affected the global flux of biota associated with transiting ships. As a minimum, opening of this passageway resulted in different trade routes, altering transit times as well as surrounding environmental conditions and voyage conditions. In addition, access to the canal likely affected the source and recipient ports for some commodities. Each of these changes, operating alone and in combination, can affect the biota transferred by ships.

Any changes in geographic route or ports will obviously affect the species assemblage that can be moved by ships, either in ballast tanks or on outer surfaces. Opening a new trade route or adding a new port is likely to result in changes not only to species composition but also relative abundances encountered by ships, affecting the initial colonization of ships and possibly the fate of organisms during transit. While the Panama Canal has surely caused a shift in both species composition and abundance of ship borne biota, the scope of such change has not been evaluated to date.

Independent of colonization of ships, the condition and survivorship of organisms will be strongly affected by voyage duration and environmental conditions encountered. The Panama Canal was built to reduce transit time between ports. Survivorship in ballast tanks is time-dependent, and past studies have shown that species from many taxonomic groups decline in abundance during voyages (Gollasch et al. 2000, Wonham et al. 2001, Verling et al. 2005). Thus, survivorship in ballast tanks should increase with reduced voyage duration, resulting in a higher density of organisms at the end of voyages, controlling for other factors (see Cohen, Panama Canal chapter III for further discussion). Although we are not aware of similar studies for time-dependent mortality for biota on the hulls of vessels, we expect a similar pattern to exist.

The rate of decline during voyages will depend upon surrounding environmental conditions, which are also affected by route. For ballasted communities, large differences in survivorship rates may exist between transits in tropical water versus high latitudes, especially if ambient conditions approach thermal tolerance limits. Although physically isolated from the environment, ballast tanks often acclimate to outside conditions experienced during voyages (Wonham et al. 2001, Gollasch et al. 2000, Ruiz unpubl. data).

The same general principles apply to organisms on the outer surfaces of vessels, and it may be that exposure to freshwater within the Panama Canal is particularly stressful for many organisms. Unlike biota in ballast tanks, these organisms are exposed to a change from full seawater to freshwater upon entering the canal. They must be able to withstand freshwater exposure for the period of transit (6-12 hours) and then acclimate again to full seawater. These rapid changes in salinity may serve as a strong biocide, actually removing many species from hulls (see however Rubinoff and Rubinoff 1969). On the other hand, there is some evidence that rapid changes in environmental conditions (especially temperature) can induce spawning (Minchin & Gollasch 2003), which may increase propagule supply to surrounding areas.

To our knowledge, the dynamics of biota associated with ships transiting the Panama Canal have not been measured. It would be especially informative to take such measures along multiple voyage routes, especially to examine the effect of pre- and post-canal routes on (a) the initial biotic content and (b) survivorship functions for both ballast and hull communities.

On balance, it is difficult at the present time to quantify exactly how the Panama Canal has affected the global flux of biota. The nature of organism transfers certainly changed with associated shifts in route, transit time, and environmental conditions. Furthermore, invasions inevitably resulted from post-canal shipping traffic, given the overall importance of ship-mediated transfers (see discussion in Panama Canal chapter III). Whether the magnitude of species movement and invasions is greater than would have occurred without the canal remains a challenging question.

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