



Temporal and spatial distribution of floating objects in coastal waters of central–southern Chile and Patagonian fjords

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ABSTRACT

Floating objects are suggested to be the principal vector for the transport and dispersal of marine invertebrates with direct development as well as catalysts for carbon and nutrient recycling in accumulation areas. The first step in identifying the ecological relevance of floating objects in a specific area is to identify their spatio-temporal distribution. We evaluated the composition, abundance, distribution, and temporal variability of floating objects along the continental coast of central–southern Chile (33–42°S) and the Patagonian fjords (42–50°S) using ship surveys conducted in austral winter (July/August) and spring (November) of the years 2002–2005 and 2008. Potential sources of floating items were identified with the aid of publicly available databases and scientific reports. We found three main types of floating objects, namely floating marine debris (mainly plastic objects and Styrofoam), wood (trunks and branches), and floating kelps (*Macrocystis pyrifera* and *Durvillaea antarctica*). Floating marine debris were abundant along most of the examined transects, with markedly lower abundances toward the southern fjord areas. Floating marine debris abundances generally corresponded to the distribution of human activities, and were highest in the Interior Sea of Chiloé, where aquaculture activities are intense. Floating wood appeared sporadically in the study area, often close to the main rivers. In accordance with seasonal river run-off, wood was more abundant along the continental coast in winter (rainy season) and in the Patagonian fjords during the spring surveys (snow melt). Densities of the two floating kelp species were similar along the continental coast, without a clear seasonal pattern. *M. pyrifera* densities increased towards the south, peaking in the Patagonian fjords, where it was dominant over *D. antarctica*. Densities of *M. pyrifera* in the Patagonian fjords were highest in spring. Correlation analyses between the abundances of floating objects and the distance to the nearest sources were generally non-significant, suggesting that post-supply processes affect the distribution of the floating objects in the study region. The identification of several major retention zones supports this idea. Accumulation areas of floating objects appear to be more common in the fjord zones. In general, the results underscore the abundance of floating objects throughout the study region and the fact that floating marine debris sources are mostly local, whereas floating algae may be dispersed over greater distances. Future studies should focus on the ecological role of floating objects in biota dispersal and nutrient cycling.

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1. Introduction

Rafting dispersal via floating objects is considered to be the most likely mechanism explaining the ample geographic range, disjunct population distribution, and molecular pattern of organisms that have direct development (Johannesson, 1988; Castilla and Guíñez, 2000; Thiel and Haye, 2006). Whereas the importance

of floating objects as dispersal vehicles has been repeatedly emphasized in recent years (e.g., Waters and Roy, 2004; Donald et al., 2005; Thiel and Gutow, 2005a, 2005b; Fraser et al., 2009), the role of these items in carbon and nutrient cycling and transfer has been mostly ignored. However, epibionts on floating algae (and other floating objects) can substantially contribute to the community respiration in the open ocean (Smith et al., 1973). Furthermore, floating objects accumulated in frontal systems are thought to play an important role in nutrient recycling (e.g., Thiel and Gutow, 2005b, and references therein). In order to evaluate the role of floating objects in species dispersal and biogeochemical cycles, it is important to first understand the

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factors that drive their abundance and distribution, which may vary substantially throughout the world's oceans.

The most common floating objects of natural origin are macroalgae, wood, seeds, land plants, and volcanic pumice (Jokiel, 1990; Maser and Sedell, 1994; Worcester, 1994; Hobday, 2000; Nelson, 2000). Floating anthropogenic objects are mainly plastics; these are usually denominated floating marine debris (FMD; Coe and Rogers, 1997; Williams et al., 2005). Some natural items have a high nutritional value for rafting organisms, whose feeding activity reduces the floating potential and persistence of floating objects at the sea surface (Vandendriessche et al., 2007; Rothäusler et al., 2009). On the other hand, some anthropogenic items of abiotic origin (e.g., plastics and buoys) have no food value for travelers. Since these items are not consumed, they persist for long periods at the sea surface, potentially transporting travelers over extensive distances (Barnes, 2002; Barnes and Fraser, 2003; Astudillo et al., 2009).

Spatial and temporal supply dynamics influence the raft abundance in particular areas. Sources of floating objects are often highly localized (e.g., rivers, human population centers, natural kelp forests). The temporal supply of floating objects also varies, and they might appear in high densities during some periods and be practically absent during others. For example,

seasonal variations in river run-off influence the supply of floating objects (e.g., wood, Johansen, 1999; plastics, Moore et al., 2002). Floating marine debris (FMD) of human origin (shipping, sea-based aquaculture operations, urban activities) often does not vary significantly over time because the supply is almost continuous (Vlietstra and Parga, 2002; Edyvane et al., 2004; Hinojosa and Thiel, 2009). The temporal supply of floating macroalgae can be highly variable, often related to algal growth seasons. For example, in coastal waters along the West Pacific, floating *Sargassum* is very abundant in spring and summer (due to fragmentation during the growth season) but almost absent in winter (Deysler and Norton, 1982; Kingsford, 1992; Hirata et al., 2001). On the other hand, no seasonal variation was observed for large rafts of the giant kelp *Macrocystis pyrifera* in the coastal waters of California, which might be due to the high supply of floating algae after storms (Kingsford, 1992; Hobday, 2000). In general, macroalgae and wood appear to enter the coastal waters on a seasonal basis, whereas anthropogenic floating items are continuously supplied.

Once at sea, floating objects are at the mercy of currents, winds, and particular oceanic features such as fronts, tides, and waves. Ocean currents influence long-term movements, whereas wind and coastal fronts drive short-term or local dispersal and

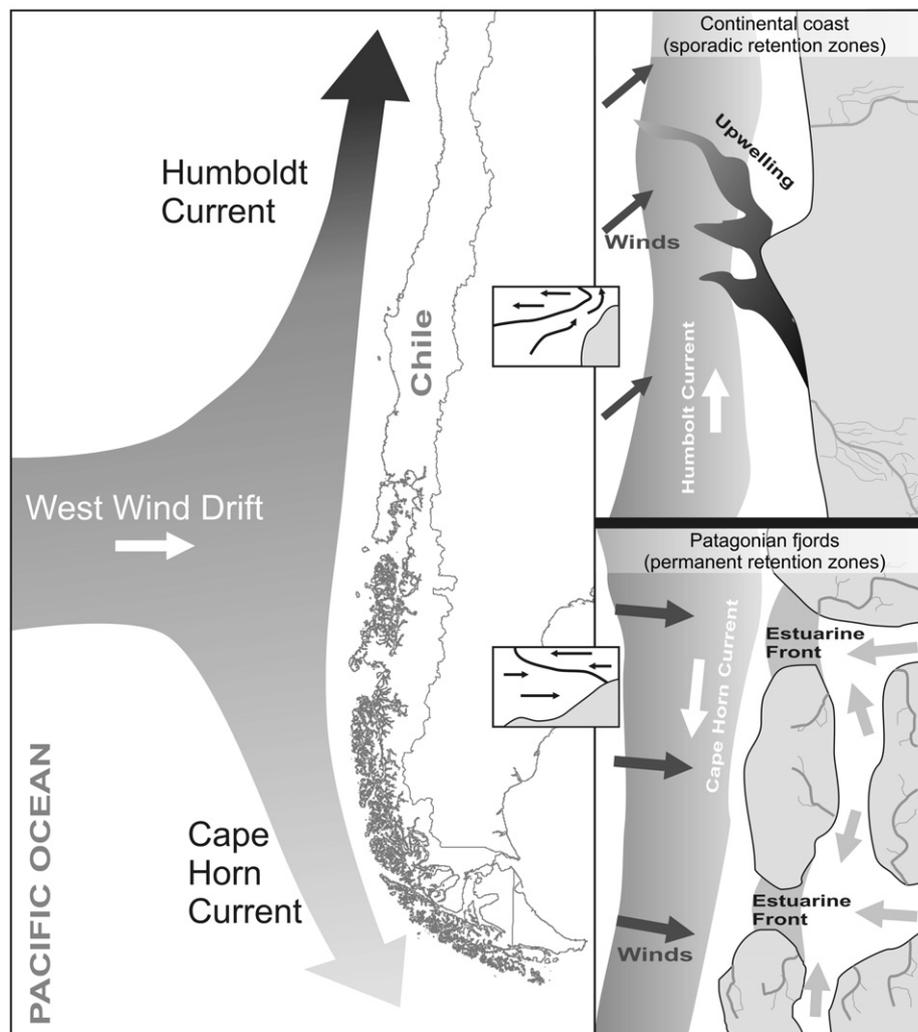


Fig. 1. Main oceanographic currents along the coast of southern Chile and conceptual model of the main oceanographic features along the continental coast of central-southern Chile and in the Patagonian fjords. Small inserts exemplify the interaction between the two main water masses in each area. General oceanographic features of the SE Pacific based on Acha et al. (2004) and for the Patagonian fjords after Sievers and Silva (2008); for additional details, please, see those references.

sink processes. Winds can have a direct effect on more buoyant floating items (e.g., Segawa et al., 1962; Astudillo et al., 2009), as shown by wind-induced accumulations of floating algae (Woodcock, 1993; Hu, 2009). Several studies have suggested that trajectories and velocities of floating objects are related to ocean currents (e.g., Kubota, 1994; Martinez et al., 2009). Floating objects are often accumulated in particular oceanic features such as coastal and estuarine fronts, upwelling systems, or eddies (Kingsford, 1995; Acha et al., 2003; Valle-Levinson et al., 2006; Komatsu et al., 2007). If retained for extended periods in these accumulation areas, floating objects can lose their buoyancy or run ashore (e.g., pushed by winds), thereby being removed from the local pool of floating items.

The abundance of rafts in a specific region strongly depends on supply (e.g., rivers, human population, kelp forests), accumulation (frontal systems), and sink processes (degradation, stranding). The geomorphology of the coastline, climatic conditions (oceanography, meteorology), and spatial distribution of human activities strongly affect these dynamics. Highly sculptured coastlines with many islands will have a broad range of widely dispersed sources but also many local retention zones. In contrast, straight coastlines are expected to have a limited number of localized sources and few, if any, retention zones. For example, a stable salinity front has been reported in estuaries and fjord systems (Acha et al., 2003, 2008; Valle-Levinson et al., 2006). Similarly, stable retention zones (e.g., eddies) present in water streaming around geological formations such as islands, seamounts, and peninsulas may retain floating objects (e.g., Kingsford, 1995). Along straight coastlines, superficial convergence zones are sporadically induced by moderate winds, internal waves, or upwelling processes (e.g., see Acha et al., 2004; Hu, 2009; Miller, 2009). Thus, we can expect different spatio-temporal dynamics of floating items along these two types of coastlines.

The continental coast of central–southern Chile and the Patagonian fjords offers an excellent model scenario for exploring whether the spatio-temporal distribution of floating items is indeed affected by the coastline (see Fig. 1). Along the continental coast of central–southern Chile, floating objects are spilled into open coastal waters, where they might be accumulated in sporadic retention zones, spread along the coast, or stranded on local beaches. In contrast, in the Patagonian fjord region, many floating objects might be retained within the estuarine channels or near islands, where they accumulate in persistent retention zones (Fig. 1). Floating objects retained in these areas might be deposited on local shores or sink to the seafloor.

The present study is a first approach toward comparing the source–sink dynamics of floating objects along two different types of coastline. Herein, we evaluate the potential sources and the spatio-temporal distribution of floating objects along the Chilean coast, and we briefly discuss the ecological implications.

2. Materials and methods

2.1. Study area

This study was conducted in central–southern Chile (33–42°S) and in the northern–central Patagonian fjords (42–50°S) from 2002 to 2005 and in 2008. In most parts of central–southern Chile, the coastline is relatively straight with few coastal inlets and bays. Several Andean rivers with seasonally varying run-off (highest in winter, Correa and Gross, 2008) bring wood and anthropogenic debris to coastal waters (e.g. Bravo et al., 2009). In contrast, the Patagonian fjords feature a highly sculptured geomorphology with many gulfs, islands, channels, and fjords. In this area, shorter rivers with intense run-off during the snow melt (mainly in spring

and summer) contribute large volumes of freshwater to the system (Niemeyer and Cereceda, 1984; Calvete and Sobarzo, in this issue).

An important proportion (80%) of the Chilean human population is concentrated in central–southern Chile between 33°S and 42°S and only 3% live in the Patagonian fjords (INE, 2005). However, in recent decades, the Patagonian fjords have experienced explosive development of salmon and mussel aquaculture, mainly in the Interior Sea of Chiloé and Los Chonos Archipelago (FAO, 2007; SERNAPESCA, 2009). Extensive kelp forests of *Durvillaea antarctica* and *M. pyrifera*, the two main floating seaweeds, are reported along the continental Chilean coast and in the Patagonian fjords (Dayton, 1985; Hoffmann and Santelices, 1997; Sielfeld, 1997; Buschmann et al., 2004, 2006).

The oceanographic processes driving the distribution of floating objects differ substantially between the continental coast and the Patagonian fjords. In central–southern Chile, frontal systems are driven by stochastic processes such as upwelling, internal waves, and wind-induced features (e.g., Figueroa, 2002; Largier, 2002; Acha et al., 2004). In contrast, estuarine circulation predominates in the Patagonian fjords (Sievers and Silva, 2008), with persistent fronts in particular zones (e.g., Córdova and Balbontín, 2006; Landaeta and Castro, 2006a, 2006b; Molinet et al., 2006) (Fig. 1).

2.2. Sources of floating objects

We used publicly available databases and our own observations to identify the principal sources of floating objects in the study area. Human population centers and sea-based activities (shipping, aquaculture) were taken as the principal sources of FMD. Data on the human population in the coastal zone were obtained from the most recent national population survey in 2002 (INE, 2005). For the correlation analysis (see below), we considered all coastal human population centers with >1000 inhabitants, but for the Kawesqar fjords study area, we used the only two villages, which combined have ~500 inhabitants. Harvest data for sea-based aquaculture in 2008 were provided by the National Fisheries Service (SERNAPESCA, 2009). We also counted the number and identified the geographic position of aquaculture centers in the study area. Data are based on the list of sea-based aquaculture concessions published in September 2009 by the Chilean Fisheries Agency (<http://www.subpesca.cl>). All these concessions may not have been active during the study period, but the list offers a good indication of the geographic distribution of aquaculture activities.

Both FMD and wood enter the system via rivers. We extracted the mean annual river flow from Correa and Gross (2008) and a dataset provided by the Chilean government (www.educarchile.cl). Additionally, data for the Baker River were obtained from the environmental evaluation system for a hydroelectric project on that river (“Proyecto Hidroeléctrico Aysén”; www.e-seia.cl). Kelp forests along the Chilean coast are the main source for floating kelps. Since *D. antarctica* grows on exposed rocky shores, we estimated the extension of the exposed rocky coastline using GoogleEarth (<http://earth.google.com/>); for the Patagonian fjords, we considered the kelp belt reported by Sielfeld (1997). The number of kelp forests of *M. pyrifera* was obtained from available published information (Dayton, 1985; Sielfeld, 1997; Buschmann et al., 2004, 2006; Gutierrez et al., 2006; Mansilla and Ávila, 2007; Plana et al., 2007), personal observations, and GoogleEarth (<http://earth.google.com/>). In order to calibrate the GoogleEarth images, we initially identified several well-known kelp forests in these images.

2.3. Abundance of floating objects

Floating objects were surveyed during eight oceanographic cruises along the continental coast of central–southern Chile and in the Patagonian fjords (Fig. 2). The cruises were conducted under the research program CIMAR-Fiordo (Cruceros de Investigación Marina en Áreas Remotas) on board the RV “AGOR Vidal Gormáz”. Each year, two research cruises took place, one in austral winter (July/August) and the other in late spring (November). Each cruise lasted ~25 days. Only the spring surveys were done in 2002 and 2008. On all these cruises, three main areas were surveyed along the continental coast: Valparaíso, Concepción, and Maullin (Fig. 2). In the Patagonian fjords, the 2002 and 2003 cruises covered Los Chonos Archipelago, including Boca del Guafo, whereas in 2004 and 2005, the cruises were done in the Interior Sea of Chiloé, again including Boca del Guafo. The 2008-cruise passed through the Interior Sea of Chiloé and Los Chonos Archipelago, and an intensive survey was conducted in Kawesqar fjords (Fig. 2).

One observer surveyed the sea surface from the bridge of the research vessel during daytime navigation (~4 m above sea level, ship velocity ~10 knots). The observer recorded all floating objects (position, size, and perpendicular distance from vessel) on one side of the ship using a handheld GPS and binoculars. The perpendicular distance of each floating object from the vessel was estimated based on known distances (e.g., vessel width or length).

The side of the ship from which observations were made was chosen for each transect depending on sun position and wind direction in order to optimize survey conditions. No data were collected during adverse weather and wave conditions (rain and wind > 50 km h⁻¹).

We used the strip transect method in order to estimate the density of floating objects. Based on the number of items seen and the area surveyed (transect width and length), we estimated the density using the following equation:

$$D = N / ((W/1000) \times L)$$

where N is the number of floating objects (see below for details), W the width of the transect (in meters, see below for details), and L the total length (in km) of the transect. The transect length corresponds to the typical distance between CIMAR stations (10–40 km) or ~1 h ship travel (~20 km) on transects without oceanographic stations (along the continental coast and in 2008 from Puerto Montt to Peninsula Taitao).

We distinguished three main types of floating objects: floating anthropogenic debris (FMD; see Hinojosa and Thiel, 2009), floating natural woods (wood branches and trunks), and floating kelps (*M. pyrifera* and *D. antarctica*). In order to estimate the density of the floating objects, we used specific transect widths for each type and size of floating object. These transect widths were estimated based on a preliminary evaluation of our data: all observed floating items of a given category (FMD, wood, and

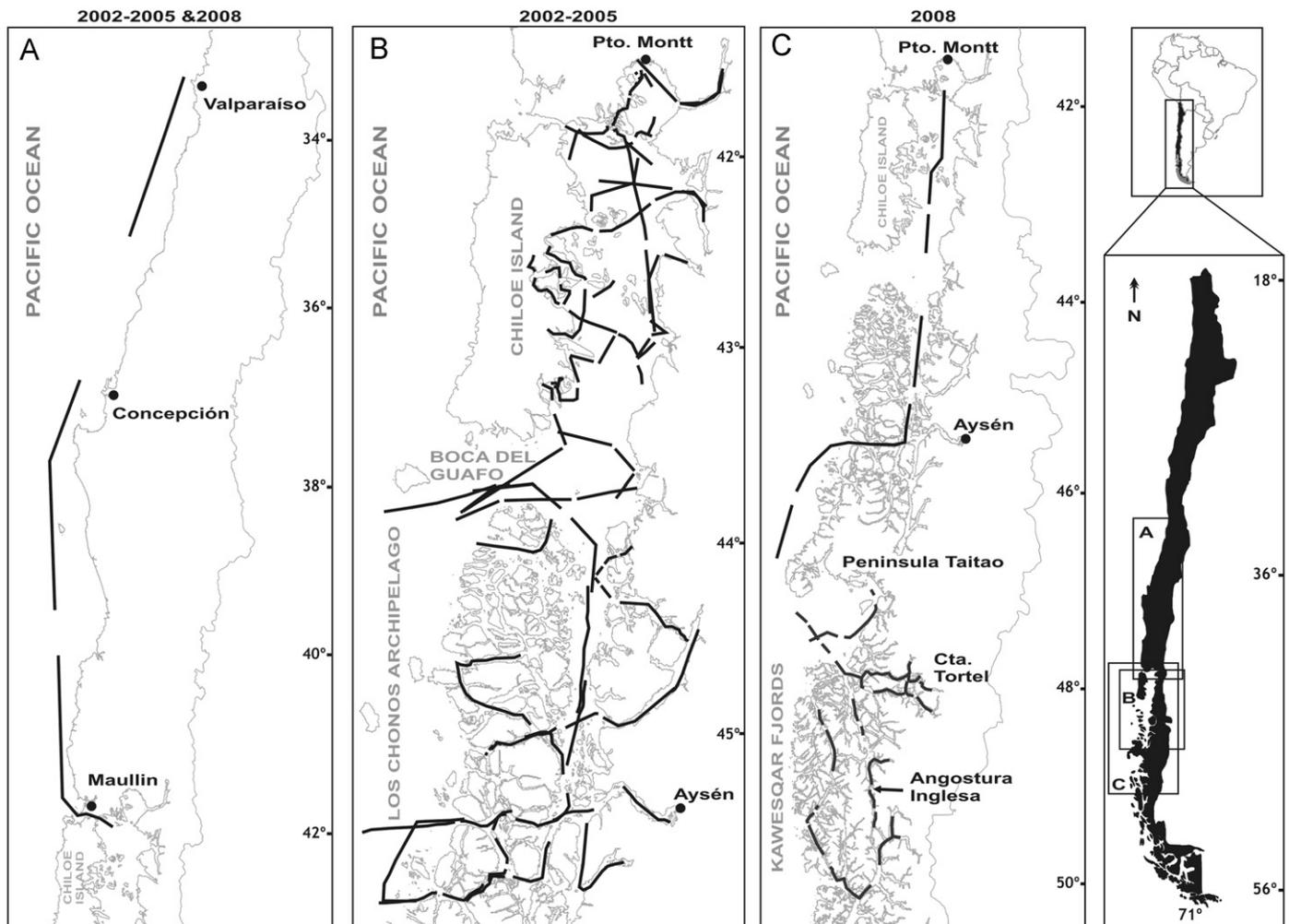


Fig. 2. General study region ((A) continental coast of central–southern Chile and (B) and (C) Patagonian fjords) and tracks surveyed in austral winter and spring of the respective study years.

different sizes of algal parts/patches) were pooled, and we identified the distance at which the probability of detection was 80–95%. Items beyond this distance were not considered. Since some items might have been overlooked within the selected transect width, this is a conservative approach and the calculated densities might slightly underestimate the total density of floating objects (for further details see Hinojosa and Thiel, 2009; Hinojosa et al., 2010). For FMD and wood, we used a transect width of 20 m. To calculate the density of floating kelp items, we used a specific width for each size category because smaller items could only be seen close to the ship; transect widths for algal parts and small, intermediate, large, and super-large patches were 5, 10, 20, 30, and 100 m, respectively. We estimated the biomass of floating kelp per km² utilizing the same equation as above, but multiplying N by the individual biomass of the respective size categories (see Hinojosa et al., 2010).

Densities of FMD and wood (numbers of items per km²) and the biomass of floating kelps (kg per km²) were calculated for each transect surveyed. We consistently surveyed seven areas, three of which were along the continental coast of central–southern Chile (Valparaíso, Concepción, Maullin) and four of which were in the Patagonian fjords (Interior Sea of Chiloé, Boca del Guafo, Los Chonos Archipelago, Kawesqar fjords; see Fig. 2). The total number of surveyed transects varied in each area ($n=3$ to 61) due to weather and daylight hours during the different cruises and the total number of cruises per study area. For the respective comparisons, we calculated the number or proportion of transects having a specific density or biomass of floating objects in each surveyed area.

2.4. Statistical analyses

To compare whether abundances of floating objects differed between the seven study areas, we pooled all transects for each type of floating object (FMD, wood, *Durvillaea*, *Macrocystis*) from all the cruises. We calculated the proportions of transects with no floating objects and with low, intermediate, and high abundances. For floating marine debris and floating wood, the low, intermediate, and high abundances were 0.1–10, 10.1–30, and > 30 items km⁻², respectively, and for floating kelps, these were 0.1–100, 100.1–1000, and > 1000 kg km⁻². These values were selected based on previous studies (Thiel et al., 2003; Hinojosa and Thiel, 2009; Hinojosa et al., 2010) to facilitate comparisons

between the seven study areas. Using contingency tables (Zar, 1999), we compared whether the proportions differed between the seven study areas.

To examine whether the abundances of floating objects depended on the distance from potential sources, we calculated the distance (km) between each transect and the nearest source, considering five kinds of sources: rivers, coastal cities, aquaculture centers, exposed rocky intertidal coasts, and *Macrocystis* kelp beds. This must be taken as a preliminary test of this idea because the approach does not take into account that sources differ in size or magnitude. Pairwise geographic distances (km) between all transects to sources were calculated using the function `earth.dist` of the library *fossil* in R (Team, 2010). We used the minimum distance to a source instead of the median or another measure of central tendency in order to minimize the boundary effects (i.e., distances may be inflated towards northern and southern extremes). The relationship between the abundance of floating objects ($\log_{10}+1$ transformed) and minimum distance to the source (\log_{10} transformed) was tested separately for each of the seven study areas using a Pearson moment-product correlation. In order to account for spatial autocorrelation, we adjusted P -values using Dutilleul's method (Dutilleul, 1993) implemented in the SAM software (Rangel et al., 2006). Negative and significant correlations may be interpreted as the abundance of floating objects being driven mostly by their proximity to sources, whereas a lack of or positive correlations may imply the existence of other post-supply processes.

3. Results

3.1. Sources of floating objects

In central–southern Chile, the human population living in the coastal zone is concentrated largely along the continental coast, with a total population of ~1,500,000 inhabitants, most in the areas of Valparaíso and Concepción (Table 1). The total population in the Patagonian fjords adds up to ~200,000 inhabitants, most of which live along the Interior Sea of Chiloé, particularly in Puerto Montt (Table 1). The human population in the coastal zones of Los Chonos Archipelago and Kawesqar fjords is very low (~19,500 and ~500 inhabitants, respectively). Sea-based aquaculture is found mainly in the Interior Sea of Chiloé, where, in 2008, ~70% of the national salmonids and ~99% of the bivalves (mainly

Table 1
Main sources of floating objects along the continental coast of central–southern Chile (Valparaíso, Concepción, Maullin) and in the Patagonian fjords (Chiloé, Guafo, Los Chonos, Kawesqar fjords).

	Rivers		Inhabitants censo 2002		Sea and estuarine aquaculture				Durvillaea (rocky shore)	Macrocystis
	No. of rivers	Mean annual discharge m ³ s ⁻¹	No. of Coastal cities	No. of people (thousands)	Salmonids		Bivalves			
					1000 tons harvest 2008	No. centers (2008)	1000 tons harvest 2008	No. centers (2008)	Lineal kilometers	No. kelp forests
Valparaíso	3	305 (W)	3	647	0	0	0	0	128	9
Concepción	5	1924 (W)	9	770	0	1	0.1	40	185	15
Maullin	4	1040 (W)	2	159	?	5	0.2	47	256	18
I.S. Chiloé	5	1003 (S)	3	195	321	474	190	890	0	57
B. Guafo	0	0	0	1.4	0	0	0	0	~70	13
Los Chonos A.	4	1361 (S)	1	19.5	156	526	< 0.1	5	~700	22
Kawesqar F.	3	1449 (Su)	0	0.5	0	0	0	0	~850	42

Data on river discharge (mean annual m³ s⁻¹) from Niemeyer and Cereceda (1984), Correa and Gross (2008), "Proyecto Hidroeléctrico Aysén" (www.e-seia.cl), and a Chilean government site (www.educarchile.cl). Seasonal maximal discharge (W=winter, S=spring, Su=summer). Data on human populations are based on the most recent national survey in 2002 (INE, 2005). Aquaculture activity taken from FAO (2007), SERNAPESCA (2009), and the Chilean Fisheries Agency (<http://www.subpesca.cl>). Habitats for *Durvillaea* (exposed rocky shore) based on GoogleEarth (<http://earth.google.com/>) and Sielfeld (1997). Number of *Macrocystis pyrifera* kelp forests based on Dayton (1985), Buschmann et al. (2004, 2006), Gutierrez et al. (2006), Mansilla and Ávila (2007), Plana et al. (2007), personal observations, and GoogleEarth (<http://earth.google.com/>).

mytilids) were produced. In 2008, a total of ~1300 sea-based aquaculture centers were counted in the Interior Sea of Chiloé and ~500 centers were located in Los Chonos Archipelago (Table 1).

The continental coast and the Patagonian fjords contain 24 main river systems (12 rivers per region; Table 1). Their mean annual discharge fluctuates from ~32 m³ s⁻¹ (Aconcagua River in Valparaíso) to ~1000 m³ s⁻¹ (Bio-Bio River in Concepción). Along the continental Chilean coast, run-off peaks in winter, i.e., the austral rainy season (June/July). The largest river of the continental coast, the Bio-Bio, has a monthly average run-off of ~2000 m³ s⁻¹ in July (winter), ~1000 m³ s⁻¹ in November (spring), and ~300 m³ s⁻¹ in January (summer). Run-off from the rivers in the Patagonian fjords is highest after the snow melt, i.e., in late spring and summer. In the fjord areas, precipitation varies seasonally, and the winter low (5 mm per day) is doubled in spring–summer. Accordingly, the largest Patagonian river, the Baker, has a monthly average run-off of ~650 m³ s⁻¹ in winter and the maximal run-off in summer (~1300 m³ s⁻¹). The run-off from many rivers in the Patagonian fjords remains unquantified. Altogether, the continental Chilean coast has an annual average river run-off of ~3300 m³ s⁻¹, whereas river run-off in the Patagonian fjords reaches > 3800 m³ s⁻¹.

Together, the continental and Patagonian fjord coastlines have a total of ~570 and ~1600 km of exposed rocky shores that can be inhabited by *D. antarctica* (Table 1). Presently available

information (Dayton, 1985 and personal observations) suggests that *D. antarctica* does not grow along the shores of the Interior Sea of Chiloé and the interior fjords and channels. A total of 30 *M. pyrifera* kelp forests were identified along the continental coast and 134 kelp forests were recognized in the Patagonian fjords (Table 1, see also below).

3.2. Distribution of floating objects

Floating marine debris (FMD) was present on most transects surveyed along the continental coast, with some exceptions. No FMD was observed in winter 2004 off Valparaíso or spring 2004 off Maullin (Fig. 3). Transects with high densities of FMD were persistently found in coastal waters off Valparaíso without a clear seasonal pattern (> 40 items km⁻², peaking at ~100 items km⁻² in spring 2003). In waters off Concepción, transects with intermediate densities (5–20 items km⁻²) were found throughout the years, but maximal densities (~55 items km⁻²) occurred in winter 2005 (Fig. 3). Off Maullin, transects with high densities (> 20 items km⁻²) occurred during the spring surveys of 2002, 2003, 2005, and 2008 (Fig. 3). In the Patagonian fjords, FMD showed a clear spatial distribution, with higher densities in the Interior Sea of Chiloé (> 40 items km⁻², with maximal abundances of ~300 items km⁻²; Fig. 3) and comparatively low

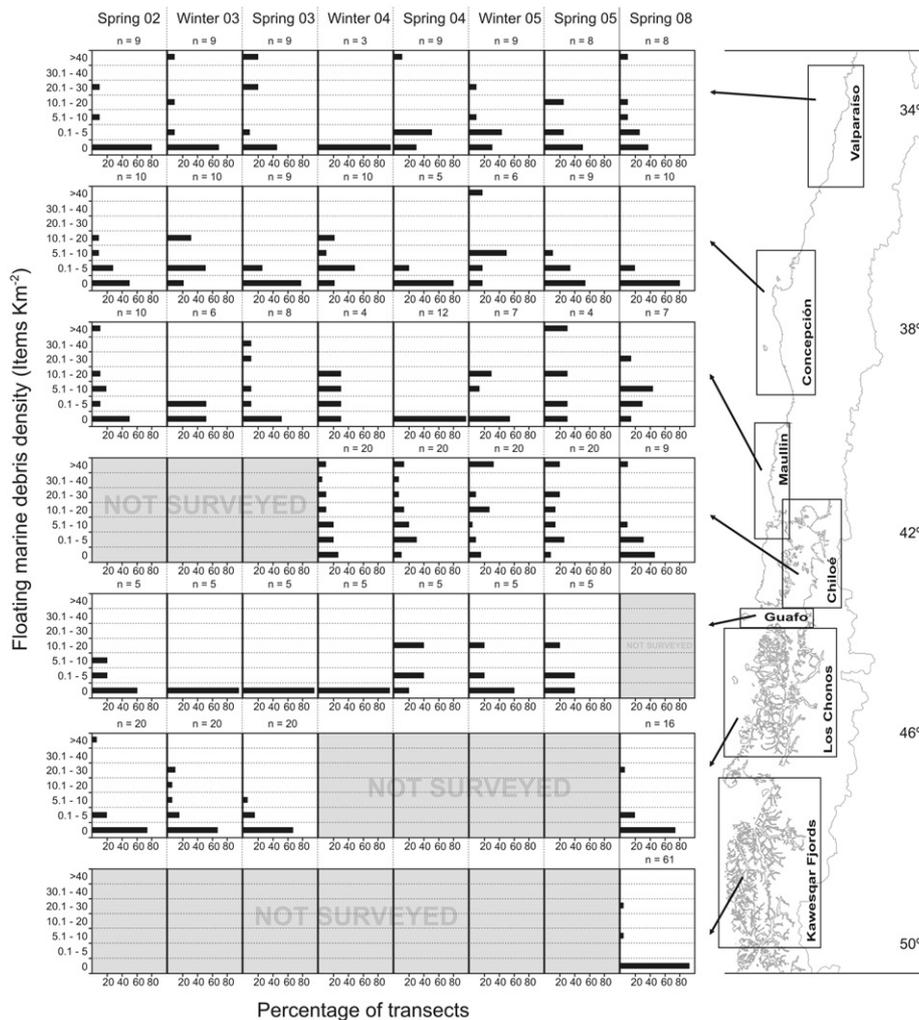


Fig. 3. Proportions of transects (X axis) with specific density (Y axis) of floating marine debris in the seven study areas. Gray areas indicate time periods during which the respective areas were not surveyed.

densities in the other fjord areas; no seasonal pattern was apparent (Fig. 3). Transects with low densities or no FMD were common in Boca del Guafo and Kawesqar fjords (Fig. 3).

Along the continental coast of central–southern Chile, floating wood (tree trunks) only occurred in low densities, but its temporal occurrence suggested a seasonal pattern. Transects with the highest densities were found off Concepción (36 items km⁻²) and Maullin (30 items km⁻²) in winter 2005 (Fig. 4). No wood was recorded along the entire continental coast during the spring surveys of 2003 and 2005. In the Patagonian fjords, the densities of floating wood were slightly higher (some transects reached densities >40 items km⁻²) but with an opposing temporal pattern. Transects with highest densities were found in spring 2002 (Los Chonos Archipelago) and spring 2005 (Interior Sea of Chiloé) (Fig. 4). Similarly, in Kawesqar Fjords, abundances were relatively high in spring 2008 (Fig. 4). Densities of floating wood in Boca del Guafo were usually low (Fig. 4).

The biomass of floating *D. antarctica* was similar to that of floating *M. pyrifera* along the continental coast (Fig. 5) and both species had highly variable spatial and temporal distributions. For example, off Concepción, transects with high biomass of *D. antarctica* (200–400 kg km⁻²) were observed in spring 2005 (Fig. 5), but in spring 2004, this species was not found at all (Fig. 5). Similarly, off Maullin, no *D. antarctica* occurred during the spring surveys of 2002 and 2005, but during the other surveys, biomass reached intermediate values. Biomass of *D. antarctica* and

M. pyrifera were similar in the two northern sectors of the continental coast. Off Maullin, biomass of *M. pyrifera* exceeded 400 kg km⁻² in spring 2003 and winter 2005, but no clear temporal pattern was observed (Fig. 5). In the Patagonian fjords, the biomass of floating kelps was considerably higher (> 1000 kg km⁻² with maximal biomass of ~4000 kg km⁻²) than along the continental coast (Fig. 5). In the fjords, *M. pyrifera* was clearly more abundant than *D. antarctica*, which was only found along a few transects in the Interior Sea of Chiloé. In contrast, in the sectors Boca del Guafo, Los Chonos Archipelago, and Kawesqar fjords, values of floating *D. antarctica* biomass were similar to those found along the continental coast, without any clear seasonal pattern. In the Interior Sea of Chiloé and Boca del Guafo, the highest biomass of floating *M. pyrifera* was observed. Transects with higher biomass occurred consistently in spring, but this temporal pattern was not found in Los Chonos Archipelago (Fig. 5).

3.3. Cross-regional comparison

At present, wood is one of the least common floating items along the Chilean coast. The giant kelp, *M. pyrifera*, has the highest biomass/density, followed by FMD and *D. antarctica* (Fig. 6). The proportion of transects with particular abundances of floating items differed between the study areas ($P < 0.0001$ for each type of

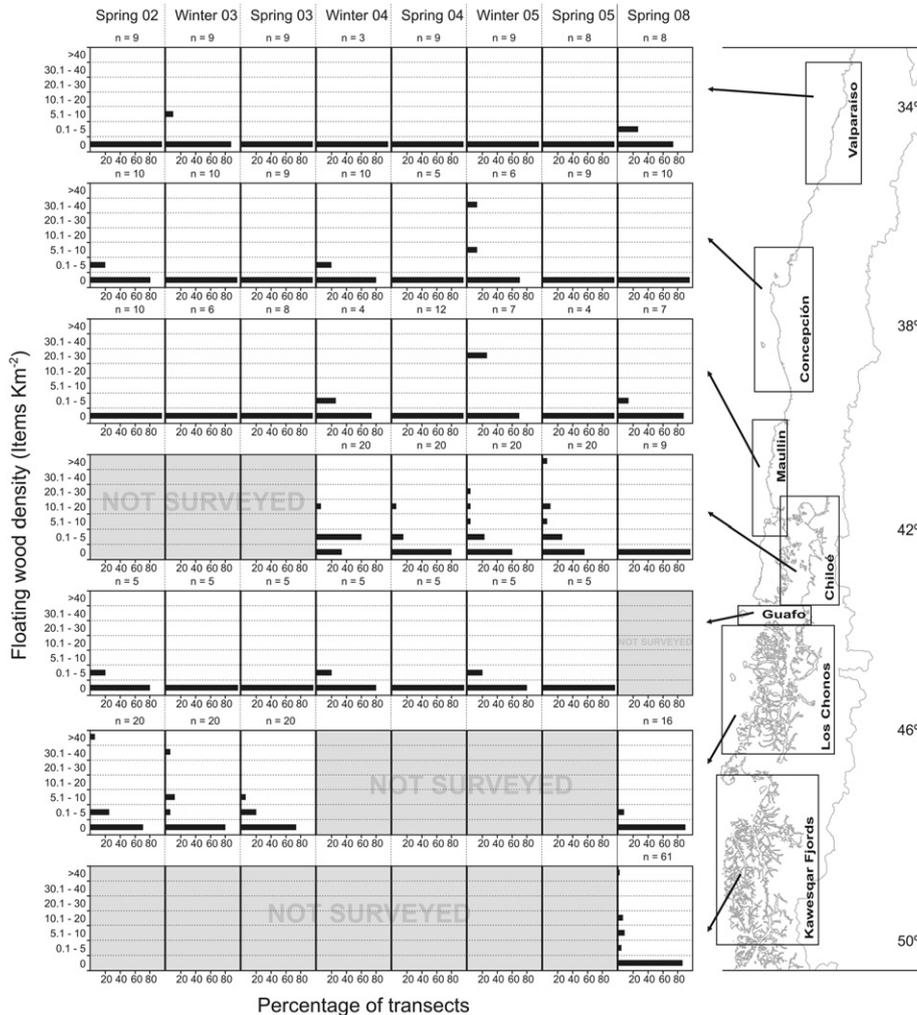


Fig. 4. Proportions of transects (X axis) with specific density (Y axis) of floating wood in the seven study areas. Gray areas indicate time periods during which the respective areas were not surveyed.



Fig. 5. Proportions of transects (X axis) with specific density (Y axis) of floating kelps (black bars for *Durvillaea antarctica* and gray bars for *Macrocystis pyrifera*) in the seven study areas. Gray areas indicate time periods during which the respective areas were not surveyed.

floating object; Fig. 6). FMD was moderately abundant along the continental coast (Fig. 6). In the Patagonian fjords, a clear latitudinal pattern was observed with continuously decreasing proportions of transects with high and intermediate abundances of FMD from the Interior Sea of Chiloé towards Kawesqar fjords (Fig. 6). As expected, a higher proportion of transects with floating wood was found in the fjord region (mainly in the Interior Sea of Chiloé) than along the continental coast. The proportion of transects with low and intermediate biomass of *D. antarctica* was similar along the continental coast and in the fjord region; in the Interior Sea of Chiloé, < 10% of all surveyed transects had any *D. antarctica* (Fig. 6). Biomass of floating *M. pyrifera* along the continental coast increased in a southward direction; throughout the fjord region, > 60% of all transects had *M. pyrifera* and about 10% of the transects had very high biomass of this macroalga (Fig. 6).

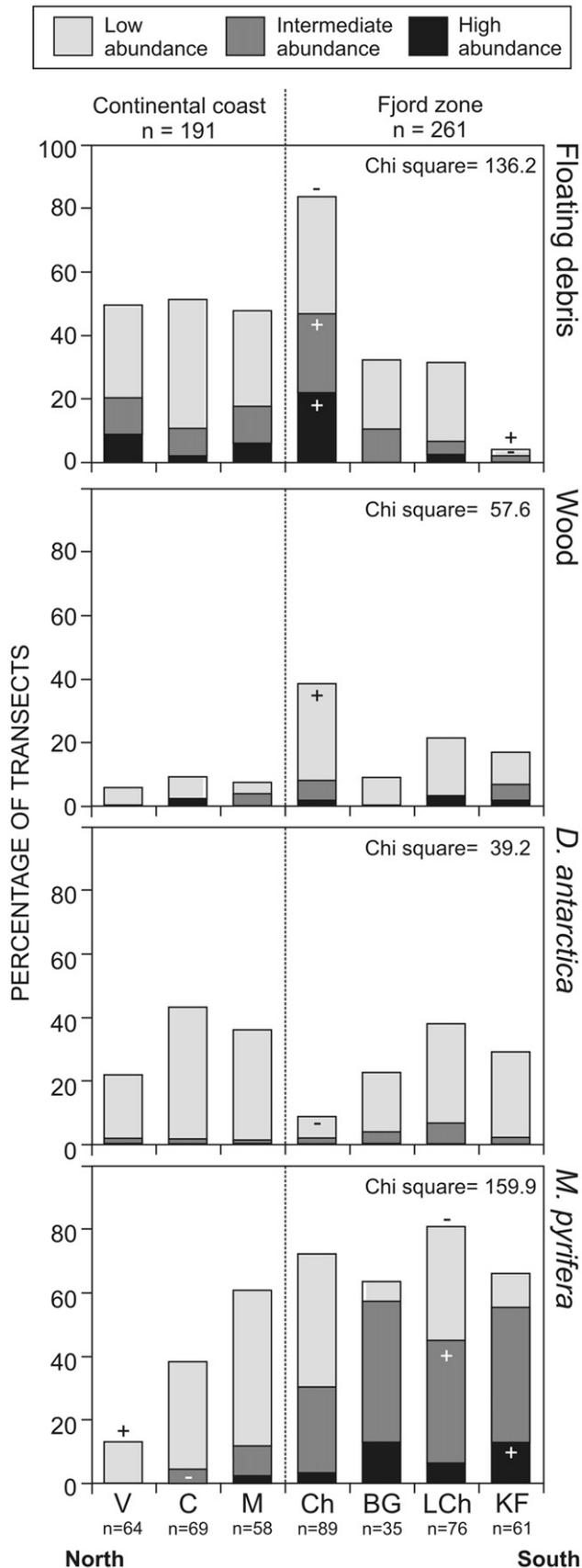
3.4. Source and sink dynamics

The correlation analyses between the abundances of each floating object and the minimum geographic distances to their respective sources showed that most tested relationships were

not significant (Table 2). The proportion of negative and positive correlations (irrespective of their significance) did not depart from a null 50:50 ratio (χ^2 test, $\chi^2=2.30$, $P=0.13$); overall, this suggests that floating objects are transported away from sources by currents and winds. However, for a few items and sectors, significant correlations were observed, hinting at the importance of local sources. FMD in Valparaíso was closely related to nearby rivers and cities, and in the Interior Sea of Chiloé, it was related to aquaculture centers (Table 2). Wood was related to rivers and cities in Kawesqar fjords, *D. antarctica* was associated with the rocky intertidal coast off Valparaíso, and *M. pyrifera* with kelp forests off Maullín (Table 2). Mostly, though, floating objects were not significantly related to local sources, indicating that post-supply processes affect the distribution of floating objects at sea.

Post-supply transport of floating items is further supported by the observation of several major retention zones (Figs. 7 and 8). Along the continental coast, the Bio-Bio upwelling front off Concepción appears to accumulate all types of floating objects (Fig. 7). Within the Patagonian fjords, floating algae are accumulated in the oceanic openings of the large inlets north and south of Chiloé (Fig. 8). High accumulations of *M. pyrifera* are also observed in the large channels of the Kawesqar fjords

(Fig. 8). Interestingly, in these retention zones, *D. antarctica* is often found more towards the interior of the channels than *M. pyrifera* (Fig. 8).



4. Discussion

In general, densities and biomasses of floating objects along the coasts of central and southern Chile are similar to those reported for other parts of the world's oceans (Thiel and Gutow, 2005a). Overall, abundances in the Patagonian fjords were slightly higher than along the continental coast, possibly due to higher supplies and/or longer residence times. Our results suggest that the abundance of floating objects in some study areas is closely linked to their spatial and temporal supply, whereas, in other areas, post-supply processes redistribute them throughout and beyond the study area. Wood and FMD appear to be more closely linked to local sources than macroalgae. Longer residence times of floating macroalgae at the sea surface may facilitate their accumulation in particular retention zones (see e.g., Acha et al., 2004), several of which were identified within the study area. Retention zones appear to be more common in the Patagonian fjords than along the continental coast, suggesting that local oceanography has a strong influence on the dynamics of floating macroalgae.

4.1. Floating marine debris: sources and sinks

Floating marine debris (FMD) has been reported in all major oceans and coastal zones throughout the world (Coe and Rogers, 1997; Gregory and Andrady, 2003). Generally, FMD abundances are highest in coastal waters at mid- and low latitudes (from 50°N to 40°S). Extreme values of > 2000 items km⁻² have been reported for enclosed waters such as the Mediterranean Sea or sheltered bays in Indonesia (Morris, 1980; Uneputtu and Evans, 1997). Typical FMD abundances for open coastal waters range from 0.01 to 25 items km⁻² (Thiel and Gutow, 2005a). Our results largely confirm this pattern and, furthermore, underline the strong relationship between sources and the distribution of FMD at sea (e.g., high abundances of FMD close to large cities or near aquaculture centers).

The supply of FMD to coastal waters depends mostly on the spatial distribution of human activities, which differ substantially between the continental coast and the Patagonian fjords. Human activities also show a strong gradient from north to south (Table 1). Human population centers and rivers appear to play a main role in the FMD supply along the continental coast, whereas the abundant aquaculture centers contribute high abundances of FMD in the northern part of the Patagonian fjords (see also Hinojosa and Thiel, 2009). The north-south gradient is particularly evident within the fjord region itself, as reflected in the decreasing aquaculture intensity from Chiloé to Los Chonos and Kawesqar fjords (Fig. 8). Similar gradients of population density and human activities are observed in other parts of the world (Tasmania, New Zealand, NE Pacific, Norway) where human populations concentrate along straight coastlines and decrease in adjacent fjordlands the farther one moves away from the straight continental coast and its extensive road networks.

Fig. 6. Proportions of transects with low, intermediate, and high abundances of different floating objects in each of the seven study areas. For floating marine debris and for floating wood, the low, intermediate and high densities were 0.1–10, 10.1–30, and > 30 items km⁻², respectively. For floating kelps, the low, intermediate, and high biomass were 0.1–100, 100.1–1000, and > 1000 kg km⁻², respectively. Study areas: V=Valparaíso, C=Concepción, M=Maullín, Ch=Interior Sea of Chiloé, BG=Boca del Guafo, LCh=Los Chonos Archipelago, and KF=Kawesqar fjords. The results of four contingency tables for each type of floating object indicated that the frequency of transects with specific abundances was different in each surveyed area; $P < 0.0001$, critical value of Chi square (0.05, 18)=28.9. (+) and (-) represent the observed frequencies above and below (Chi square values > 10, respectively) the expected frequencies.

Table 2

Correlation (Pearson moment-product) between abundance of floating objects in each transect and the geographic distance to the nearest source in each of the seven study areas. *P*-values between parentheses were adjusted to account for spatial autocorrelation. Significant values in bold. In some cases, the frequency of objects was low ($n < 7$) and correlations were not estimated (n.e.).

Region	Item	Rivers		Cities		Aquaculture centers		Rocky intertidal coast		Kelp forests	
		Correlation	<i>P</i> -value	Correlation	<i>P</i> -value	Correlation	<i>P</i> -value	Correlation	<i>P</i> -value	Correlation	<i>P</i> -value
Valparaíso	Debris	-0.53	0.03	-0.67	0.01	0.33	0.23				
	Wood	n.e.		n.e.		n.e.					
	Durvillaea							-0.55	0.04	0.12	0.29
	Macrocystis										
Concepción	Debris	-0.15	0.17	-0.16	0.26	-0.17	0.19				
	Wood	n.e.		n.e.		n.e.					
	Durvillaea							-0.02	0.91	-0.14	0.28
	Macrocystis										
Maullin	Debris	-0.05	0.63	-0.15	0.27	-0.21	0.16				
	Wood	0.12	0.17	0.10	0.29	0.10	0.41	-0.19	0.06		
	Durvillaea									-0.42	0.04
	Macrocystis										
I.S. Chiloe	Debris	0.08	0.68	-0.34	0.07	-0.43	0.02				
	Wood	-0.15	0.23	0.12	0.32	-0.10	0.41				
	Durvillaea							-0.11	0.33	0.03	0.81
	Macrocystis										
B. Guafo	Debris	-0.29	0.11	0.01	0.95	0.07	0.66				
	Wood	n.e.		n.e.		n.e.					
	Durvillaea							0.19	0.23	-0.04	0.80
	Macrocystis										
L. Chonos A	Debris	-0.15	0.16	-0.06	0.55	0.13	0.30				
	Wood	-0.21	0.16	-0.13	0.33	-0.06	0.62				
	Durvillaea							-0.11	0.35	0.09	0.56
	Macrocystis										
Kawesqar F.	Debris	n.e.		n.e.		n.e.					
	Wood	-0.70	0.01	-0.51	0.02	-0.12	0.55				
	Durvillaea							0.12	0.38	-0.35	0.13
	Macrocystis										

During recent decades, aquaculture activities invaded the accessible parts of these fjordlands (e.g., Deutsch et al., 2007; Banta and Gibbs, 2009), providing an abundant supply of previously non-existent FMD.

Our results suggest that most FMD introduced by human activities has a short residence time in coastal waters (moved by wind) and will mostly contaminate local beaches. This suggestion is supported by beach surveys in which the highest FMD densities were reported on beaches near main sources of FMD, i.e. human population centers and at the mouths of large rivers (e.g., Bravo et al., 2009). However, some FMD (e.g., plastics, Styrofoam, buoys with high floating potential) may escape the local supply-sink dynamics and, due to its high persistence at the sea surface, has the potential to travel very long distances (e.g., see Barnes and Milner, 2005).

4.2. Floating wood: sources and sinks

Floating wood is frequently mentioned as a viable rafting vehicle for a variety of wood-dwelling organisms, both of terrestrial and aquatic origin (King, 1962; Johansen and Hyyteborn, 2001; Cragg et al., 2009). Reports of floating trees come from tropical regions, temperate waters, and subpolar regions (Thiel and Gutow, 2005b and references therein). Especially in subpolar regions, large quantities of driftwood accumulate on local beaches (Johansen, 1999; Alix, 2005) but, surprisingly, data on densities of floating wood at sea are scant (for exceptions see Matsumura and Nasu, 1997; Barnes and Milner, 2005). Never-

theless, the temporal and spatial distribution of floating wood appears to be predictable and authors often relate it directly to river discharge (Gomes et al., 1998; Solana-Sansores, 2001; Castro et al., 2002). In subpolar regions, the highest supply of floating wood occurs during the snowmelt in spring and summer (Johansen, 1999; Alix, 2005), and in tropical and subtropical regions, supply is related to the rainy season and/or tropical storms (Solana-Sansores, 2001).

Our results support the conclusion that wood is mainly supplied by large river systems, despite the relatively few observations and generally low abundances found along the continental coast. The temporal occurrence of floating wood differs between the two study areas: along the continental coast of Chile (33–42°S), floating wood was more frequent in winter, whereas in the fjord region (42–50°S), it was more common in spring. This is probably related to different seasonal patterns in river run-off (see above). Erosion of unprotected shorelines and river banks during storm and flood events commonly cause tree falls in coastal waters and rivers (for the Arctic see e.g. Alix, 2005). The high proportion of transects with floating wood in the fjord region may thus be due to abundant wood supply along the extensive coastlines (mostly forested), the high proportion of forested land along river banks (Lawford et al., 1996), and the generally short distances from forests to the sea (Alaback, 1991; Vargas et al., in this issue). In the Patagonian fjords, forests were identified as an important source of terrestrial carbon (Sepúlveda et al., in this issue).

Depending on the type of wood, the persistence of floating wood at the sea surface is highly variable (Alix, 2005 and references therein). A large proportion of wood may only float

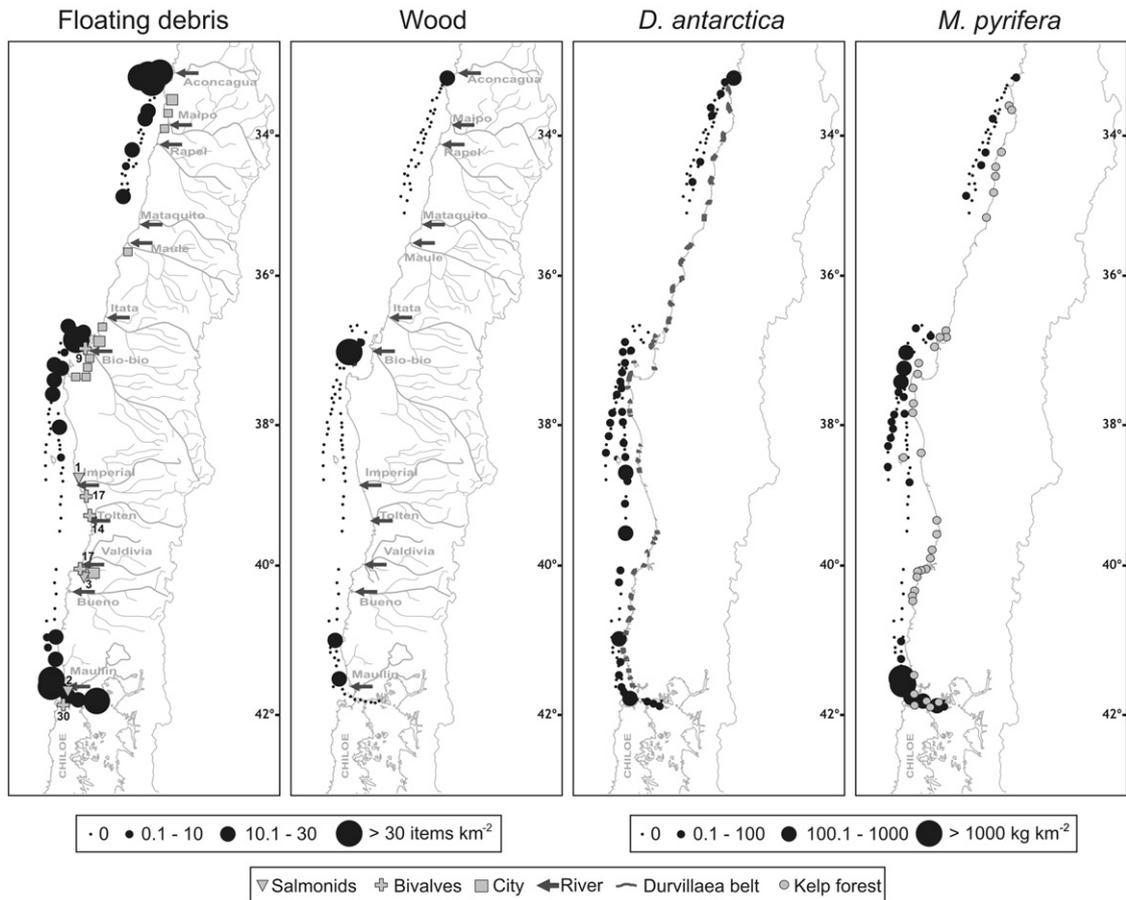


Fig. 7. Densities of floating marine debris and wood (items km^{-2}), biomass of floating kelps (kg km^{-2}), and the respective sources along the continental coast of central-southern Chile. Symbols for salmonids and bivalves represent the location with a concentration of sea-based aquaculture centers based on the list of approved concessions published in September 2009 by the Chilean Fisheries Agency (<http://www.subpesca.cl>) (numbers next to the symbols indicate the number of aquaculture centers). Data from all study years were pooled.

for relatively short periods, sinking within the immediate coastal zone (as also suggested by the significant correlation for Kawesqar fjords). Abundant wood deposits in shallow waters and the high frequency of wood in bottom trawls (I.A. Hinojosa, personal observations) are testimony to this; said deposits may also be responsible for the terrestrial signature of particulate organic matter in the fjord region (Sepúlveda et al., in this issue; Vargas et al., in this issue). Another important proportion of floating wood will end up on local beaches, again confirmed by large accumulations of driftwood on some beaches in the fjord region. Some wood persists for long periods at the sea surface and could be carried out of the study areas by the main currents, traveling longer distances, although we cannot presently determine which fraction of the floating wood that would be. Some of the floating wood observed in the Maullin and Concepción sectors may come from the fjord region. Based on the present results and the above considerations, it is hypothesized that a large proportion of floating wood in the fjord region will remain (sunken or stranded) within close vicinity of its sources. Future studies are required to test this hypothesis. Persistence time of native woods at the sea surface could be studied experimentally (e.g. Häggblom, 1982 and references therein). Sources and transport distances of floating, sunken, or stranded wood in the fjord area can also be determined with the aid of descriptive methods, e.g., dendrochronological techniques (see e.g., Johansen and Hytteborn, 2001), histology (Pailleret et al., 2007), or molecular approaches (Hurr et al., 1999).

4.3. Floating macroalgae: sources and sinks

Macroalgal beds abound in temperate coastal waters (20° – 60° in both hemispheres), where high densities of floating macroalgae have also been reported (e.g., Kingsford, 1992, 1995; Hobday, 2000; Komatsu et al., 2008). The maximum biomass (several transects had densities $> 1000 \text{ kg km}^{-2}$) in the Patagonian fjords was similar to that in other regions. Benthic macroalgae develop primarily during the annual growth season, and detachment events occur mainly between spring and fall (e.g., Kingsford, 1992). In temperate zones where algae grow continuously (albeit with seasonal peaks), no clear seasonal pattern in the appearance of floating algae has been identified, and pulses of floating algae appear mainly after storm events (e.g., Hobday, 2000). Accordingly, along the continental Chilean coast, no clear seasonal pattern of floating kelps was found. However, in the northern area of the Patagonian fjords, floating *M. pyrifera* was consistently more abundant in spring; this might be related to the stronger seasonality in this zone (Hinojosa et al., 2010), where kelp forests reach highest densities and biomass in spring/summer (Buschmann et al., 2006). At higher latitudes the maximal production of kelp forests occurs in spring/summer (Graham et al., 2007) and, consequently, one might expect floating kelp populations to show more seasonal patterns with increasing latitude.

No clear relationship was found between high abundances of floating kelp and local sources. Correlations were only significant in the Maullin area, but it is unlikely that the extremely high

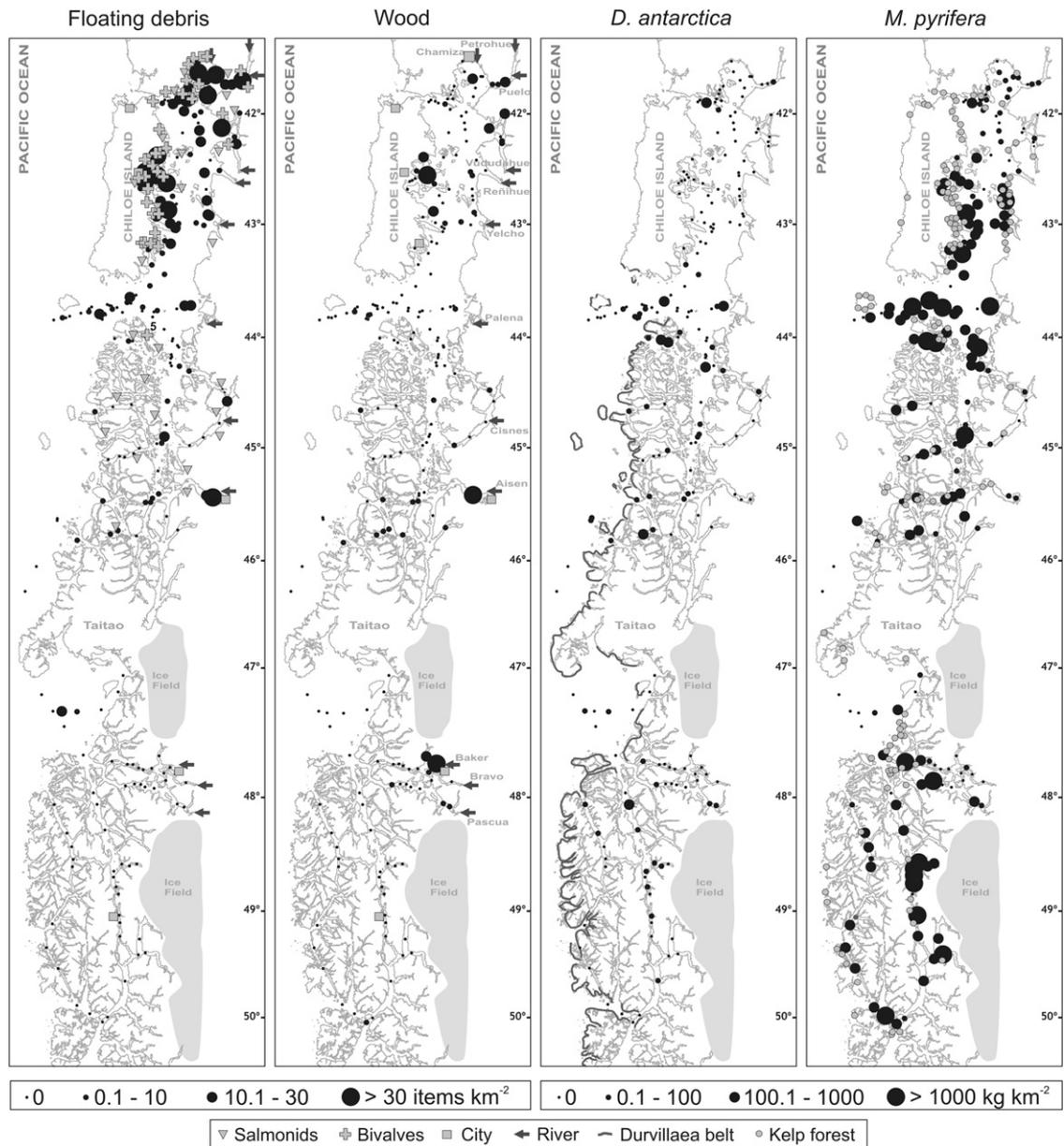


Fig. 8. Densities of floating marine debris and wood (items km^{-2}), biomass of floating kelps (kg km^{-2}), and the respective sources in the Patagonian fjords. Symbols for salmonids and bivalves represent the location with a concentration of sea-based aquaculture centers based on the list of approved concessions published in September 2009 by the Chilean Fisheries Agency (<http://www.subpesca.cl>) (each symbol represents 30 centers with the exception of the cross in Los Chonos Archipelago, which represents five bivalve centers). Data from all study years were pooled.

densities of floating *M. pyrifera* observed there could be supported by the few kelp beds in that area. Instead, it is more likely that very large rafts of *M. pyrifera* come from the Interior Sea of Chiloé. The lack of a clear relationship suggests that kelps remain floating for some time after detachment and, during that time, are dispersed by currents and wind (e.g., Harrold and Lisin, 1989). Conditions in central–southern Chile (moderate UV-radiation, sea surface temperatures ranging between 8 and 12 °C) permit long-term persistence of floating kelps at the sea surface (Rothäusler et al., 2009).

Along the continental coast, a large proportion of floating *M. pyrifera* appears to be retained in the upwelling front off Concepción, where intermediate densities are frequently observed; most of these kelps probably come from kelp beds farther south. In the Patagonian fjords, floating *M. pyrifera* are transported by the surface outflow to the oceanic openings north and south of Chiloé, where they are retained by strong western winds

(Hinojosa et al., 2010). Similar processes apply to *D. antarctica*, but due to its high buoyancy, this kelp is probably more directly affected by winds. Throughout the study region, floating *D. antarctica* were found relatively close to their sources. Their floating behavior may be similar to FMD, and most of them may quickly end up on local beaches. In the openings of the large channels (e.g., north and south of Chiloé), *D. antarctica* is pushed eastwards by the prevailing west winds, as evidenced by the comparatively high abundances observed towards the interior parts of these channels.

Our results suggest that a significant proportion of floating kelp *M. pyrifera* may be transported away from local sources. This has also been reported for floating macroalgae in the Argentinean Patagonia, Iceland, California, and Asia, among others (Helmuth et al., 1994; Ingólfsson, 1995; Hobday, 2000; Komatsu et al., 2008). If accumulated within particular retention zones, these floating kelps might contribute to rafting dispersal and to biomass transfer.

4.4. Implications and outlook

The processes driving the spatial and temporal distribution of floating items along the coast of central and southern Chile are complex. Clearly, supply plays an important role and it appears relatively predictable throughout the study region, even though episodic events (flood waters, storms, tsunamis) may disrupt normal patterns. While annual and seasonal supply follow regular patterns, our present knowledge of post-supply processes is too limited to infer how floating objects are redistributed at sea. Nevertheless, the present study reveals certain patterns that can be used to formulate specific hypotheses.

The post-supply distribution of floating items depends to a large degree on the characteristics of floating objects (Fig. 9).

Highly buoyant items (e.g., FMD, *D. antarctica*) are often found close to sources, suggesting that floating times in the study areas are comparatively short. Most likely, these floating objects are strongly affected by the prevailing westerly winds, which rapidly push them onto nearby shorelines. In contrast, wood and *M. pyrifera* are less buoyant (70–90% of their surface are under water) and are probably more directly affected by surface currents (see Harrold and Lisin, 1989). Buoyancy (and exposure to winds or surface currents) and persistence at the sea surface, thus, have a strong effect on the observed distribution of floating objects.

Overall, FMD, wood, and *D. antarctica* appear to be more closely related to sources and seasonal supplies (Fig. 9): FMD and *D. antarctica* are quickly removed by stranding, whereas most wood probably sinks to the seafloor shortly after supply.

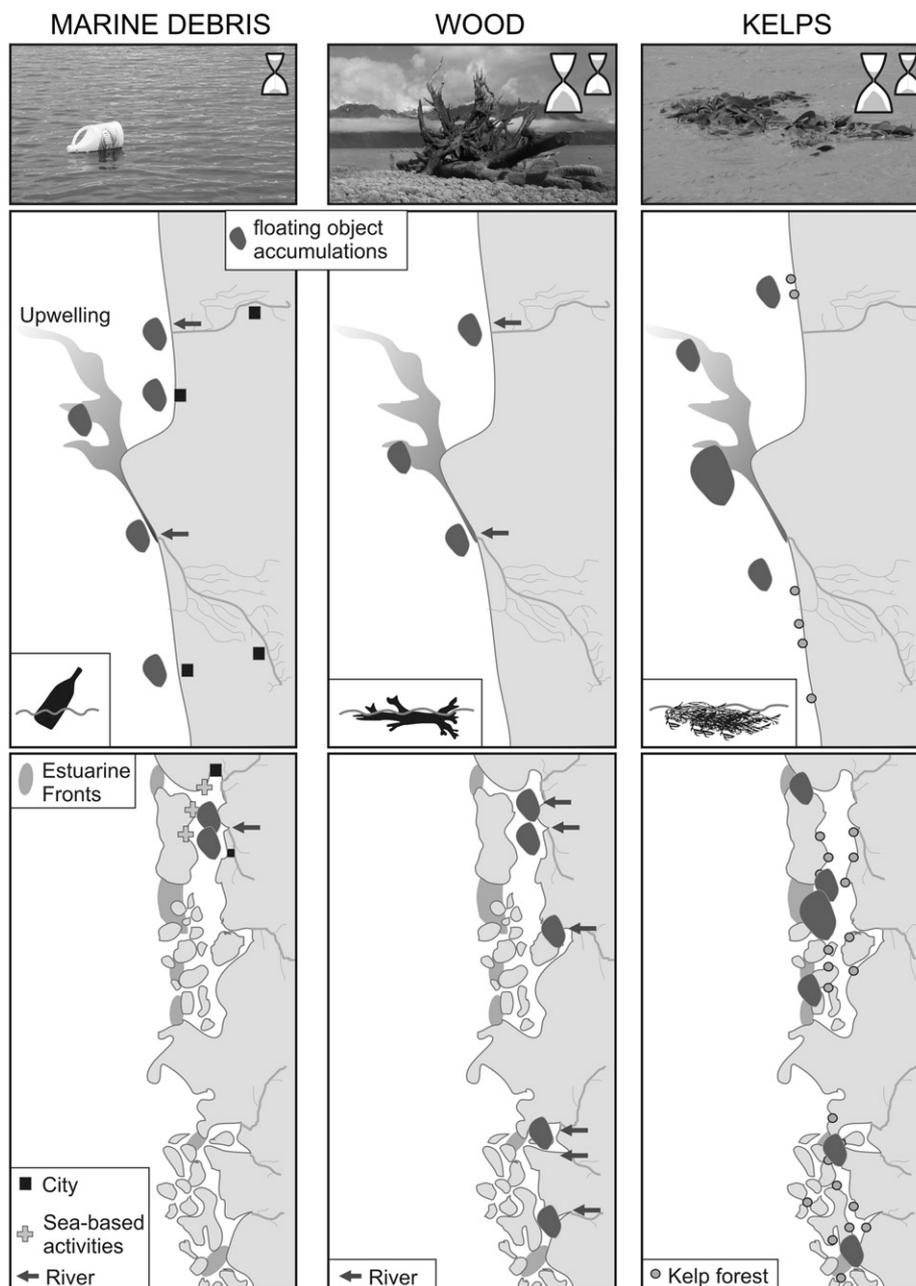


Fig. 9. Conceptual model indicating the accumulation process and the relative floating time (size of the hourglasses) of the main floating objects along the continental coast of central–southern Chile and in the Patagonian fjords. In general, floating marine debris has lower floating times than floating wood and kelp rafts, which may float for short (water-soaking wood and *Durvillaea antarctica*) or long time periods (water-resistant wood and *Macrocystis pyrifera*), respectively. Please, note that floating time and location of retention zones are directly related to wind, oceanographic features, and coastal geomorphology.

M. pyrifera may persist for longer periods at the sea surface, both due to the low buoyancy and high growth potential of rafts under the conditions in southern Chile (Rothäusler et al., 2009). During their floating trips, kelp rafts are accumulated in retention zones, which appear to play a more important role in the Patagonian fjords than along the continental coast (Fig. 9).

Patterns similar to those observed herein for floating objects along the central and southern coasts of Chile can also be expected for other coastal zones. Based on our observations, we predict that the distribution of floating objects is closely related to their buoyancy, persistence at the sea surface, local winds, and surface currents. Depending on the geomorphology of the coastline and the local oceanography, floating items might accumulate in local retention zones, where they can reach very high densities (e.g., Kubota, 1994; Komatsu et al., 2007, 2008). The high biomass of floating algae in these retention zones (often > 1000 kg km⁻²) suggests that they play an important role in the dispersal of associated fauna and in local cycles of organic matter. Future studies should explore the processes in these retention zones.

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