SPATIAL AND TEMPORAL VARIATION IN THE DIETARY ECOLOGY OF THE GLAUCOUS-WINGED GULL *LARUS GLAUCESCENS* IN THE PACIFIC NORTHWEST

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SUMMARY

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Effective use of seabirds in ecotoxicology monitoring programs ideally requires detailed knowledge of their ecology. Environment Canada recently expanded the Great Lakes Herring Gull *Larus argentatus* Monitoring Program to a national contaminants monitoring program, utilizing the Glaucous-winged Gull *L. glaucescens* on the west coast of Canada. The utility of the Glaucous-winged Gull as a marine monitoring species hinges on its consumption of a marine-based diet; however, there is a lack of recent and reliable diet data for this species. Using conventional analysis, we studied dietary ecology at two monitored colonies to elucidate adult diet before egg laying and during incubation, to investigate intra-colony dietary shifts over the breeding season, to examine inter-colonial dietary variation, and to compare findings with historical studies from the early 1970s and 1980s. Results indicate that breeding gulls forage in an opportunistic manner, with marine prey sources predominant at all colonies and breeding stages, but with a wider variety of prey types consumed in locations close to urban development. Chicks at both colonies were provisioned primarily with fish; however, variation in chick diet between 2009 and 2010 indicates that diet can vary considerably on a short time scale. The occurrence of fish fed to chicks appears to have shifted composition from herring *Clupea pallasii* in the 1980s to primarily Pacific Sand Lance *Ammodytes hexapterus* at both colonies in 2009 and 2010. Compared with historical records, gulls consumed fewer anthropogenic items and more fish in the Strait of Georgia, whereas diet off the west coast of Vancouver Island appears to have been consistently marine.

Key words: Glaucous-winged Gull, *Larus glaucescens*, diet, conventional diet analysis, biological monitoring, historical variation

INTRODUCTION

The widespread distribution of contaminants in marine environments is of global concern, particularly for those compounds that do not readily degrade and are relatively volatile, such as persistent organic pollutants (POPs) (Jones & De Voogt 1999, Tanabe 2004). POPs are a group of lipophilic compounds that accumulate in fatty tissues of organisms, leading to their bioaccumulation and biomagnification in marine food webs (Jones & De Voogt 1999, Tanabe 2004), with particularly high concentrations in piscivorous seabirds (Gilbertson *et al.* 1987, Furness & Camphuysen 1997, Gochfeld & Burger 2001, Becker 2003, Elliott & Elliott 2013). Accordingly, seabirds, including gull species, are integral components of several monitoring programs and provide data on trends, exposure pathways and effects of persistent contaminants (Newton *et al.* 1990, Elliott *et al.* 1989, 1992, 2005, Bignert *et al.* 1998, Hebert *et al.* 1999*a*, Becker *et al.* 2001, Braune 2007, Verreault *et al.* 2010, Fliedner *et al*. 2012, Burgess *et al*. 2013, Miller *et al*. 2014, 2015a, 2015b). One such program, the Great Lakes Herring Gull Monitoring Program, has successfully used the Herring Gull *Larus argentatus* since the early 1970s to track spatial and temporal trends in the distribution of many POPs (e.g. Norstrom *et al.* 1995, Hebert *et al.* 1999*b*, Gauthier *et al.* 2008, 2009). In 2006, the Environment Canada Chemical Management Plan (CMP) expanded annual gull monitoring to the national level, with the intention of tracking emerging contaminant trends in various gull species across Canada (Gebbink *et al.* 2011, Chen *et al.* 2012). As the sole larid breeding in British Columbia's coastal waters (Vermeer & Devito 1987), the Glaucous-winged Gull *L. glaucescens* is the only species used on the Pacific coast as part of this national contaminant-monitoring program.

The effective use of a seabird species as a contaminants biomonitor ideally requires detailed knowledge of its ecology, diet composition, trophic level, and migratory behaviour (Butler *et al.* 1971, Furness & Camphuysen 1997, Becker 2003, Burger & Gochfeld 2004). In particular, the use of omnivorous gull species requires a comprehensive understanding of their dietary variation. Although the biology of the Herring Gull at the Great Lakes colonies has been well researched (e.g. distribution: Moore 1976; reproductive success: Teeple 1977; energetics: Norstrom *et al.* 1986; foraging and diet: Fox *et al.* 1990, Ewins *et al.* 1994, Hebert *et al.* 1999a, 2008; abundance: Morris *et al.* 2003), a study by Gebbink *et al.* (2011) on perfluorinated compound trends at nationally monitored colonies concluded that further knowledge of dietary structure and foraging ecology of the newly added gull species is required to properly interpret CMP contaminant-monitoring data.

Studies of seabird diets have employed a range of sampling methods (Duffy & Jackson 1986, Shealer 2001, Barrett *et al.* 2007, Karnovsky *et al.* 2012). Conventional methods, often involving direct sampling of pellets and regurgitations, are known to both over- and under-represent particular prey groups, and are reflective of recent meals rather than assimilated diet (Duffy & Jackson 1986, Brown & Ewins 1996, González-Solís *et al.* 1997, Barrett *et al.* 2007, Weiser & Powell 2011). Nonetheless, these methods have the advantage of identifying specific prey items (Karnovsky *et al.* 2012) and providing insight into broad dietary trends (Furness & Monaghan 1987); as a result, they have been widely used in gull diet research to determine dietary composition (Vermeer 1982, Fox *et al.* 1990, Ewins *et al.* 1994, Kubetzki & Garthe 2003, Herrera *et al.* 2005, Ramos *et al.* 2009, Weiser & Powell 2010). More recently developed techniques, such as stable isotope and fatty acid signature analysis, are frequently regarded as advantageous, since sampling is often less invasive and allows for time-integrated estimates of diet (Barrett *et al.* 2007); however, conventional techniques still provide essential knowledge necessary to comprehensively interpret contaminants data.

Because of a lack of recent and reliable data on foraging behaviour and dietary plasticity in Glaucous-winged Gulls in Canada, it is important to re-examine their diet in order to accurately interpret trends in toxicological egg monitoring data. We investigated diet using conventional methods at two colonies on the Pacific coast of Canada in order to: (1) characterize the current feeding ecology of breeding adults before egg laying and during incubation, (2) elucidate inter-colony dietary variation, and (3) examine temporal variation, by comparing our findings with historical studies (Henderson 1972, Ward 1973, Vermeer 1982). Because dietary shifts associated with different stages in the breeding season have been previously documented in large Pacific larids (e.g. Annett & Pierotti 1989), and future monitoring may include contaminant effects on nestlings, we also examined (4) short-term intra-colonial dietary shifts over the course of the breeding season.

METHODS

Study area

Two Glaucous-winged Gull colonies were selected for sampling based on their current use in CMP toxicological monitoring and

TABLE 1
Marine invertebrate and fish prey taxa consumed by adult and chick Glaucous-winged Gulls at Mandarte and Cleland Islands during different breeding stages

	Frequency of occurrence (%)[a]									
	Pellets from adults				Regurgitations from chicks					
	Mandarte Island		Cleland Island		Mandarte Island				Cleland Island	
Food categories	**Pre-laying 2010 (n = 61)**	**Incubation 2010 (n = 17)**	**Pre-laying 2010 (n = 47)**	**Incubation 2010 (n = 0)[b]**	**Early 2009 (n = 46)**	**Late 2009 (n = 64)**	**Early 2010 (n = 54)**	**Late 2010 (n = 28)**	**Early 2010 (n = 4)**	**Late 2010 (n = 19)**
Marine invertebrates	55.7	64.7	100.0	–	6.52	4.7	–	14.3	–	10.5
Bivalves/gastropods	26.2	23.5	14.9	–	–	3.1	–	3.6	–	10.5
Chitons	3.3	–	–	–	–	–	–	–	–	–
Crabs/Shrimp	27.9	35.3	4.3	–	2.2	1.6	–	7.1	–	–
Euphausiids	–	–	–	–	2.2	–	–	–	–	–
Gooseneck barnacles	–	–	93.6	–	–	–	–	–	–	–
Errant polychaete	19.7	47.1	–	–	–	1.6	–	10.7	–	–
Sea star	–	5.9	2.1	–	4.3	1.6	–	–	–	–
Fish	39.3	29.4	–	–	89.1	81.3	96.3	96.4	100.0	94.7
Samples containing fish, n	24	5	–	–	41	52	52	27	4	18
Herring	[c]	[c]	[c]	–	7.3	11.5	1.9	3.7	–	27.8
Pacific Sand Lance	[c]	[c]	[c]	–	26.8	25.0	50.0	59.3	50.0	50.0
Salmon	[c]	[c]	[c]	–	–	1.9	1.9	–	–	–
Pricklebacks/gunnels	[c]	[c]	[c]	–	–	–	–	7.4	–	–
Midshipman	[c]	[c]	[c]	–	2.4	–	–	–	–	5.6
Unidentified/ digested	[c]	[c]	[c]	–	64.4	65.4	46.2	37.0	50.0	27.8

[a] Fish taxa represented as frequency of occurrence (%) in samples containing fish.
[b] Nest areas were surveyed for pellets but none were found.
[c] Indicates fish species were not identified in pellets.

the existence of historical information on diet (Henderson 1972, Ward 1973, Vermeer 1982). Both colonies were on small- to medium-sized, mostly treeless, offshore islands close to Vancouver Island (Vermeer & Devito 1987, Hayward & Verbeek 2008, BC Conservation Data Centre 2011). Mandarte Island (Georgia Strait/Salish Sea, BC; 48.633°N, 123.283°W) is located near urbanized areas and landfills, where the gulls may acquire anthropogenic food sources. It is currently the largest Glaucous-winged Gull colony in British Columbia (>1 800 active nests in 2009; Blight 2012), and gulls nest predominantly in meadow areas with grass cover (Henderson 1972, Vermeer & Devito 1987). Cleland Island, BC (49.167°N, 126.083°W) is a sizable colony (1400 active nests in 2010; pers. comm. Peter Clarkson 2010) located off the west coast of Vancouver Island. The colony represents a more exposed, remote site where diet has historically consisted of marine sources (Henderson 1972, Ward 1973), and gulls are restricted to nesting on the bare rock margin encompassing the island (Henderson 1972, Vermeer & Devito 1987). Designated as an ecological reserve, Cleland Island protects sensitive habitat for several seabird and marine species; accordingly, collection trips were limited to minimize disturbance.

Sample collection

To determine adult Glaucous-winged Gull diet, nesting areas were surveyed for fresh pellets (regurgitations of hard, indigestible food parts) before egg laying (i.e. during nest initiation and construction; Mandarte: 7–9 May 2010, Cleland: 10 May 2010) and during early incubation (Mandarte: 7–9 June 2010, Cleland: 1–2 July 2010). To ensure that the pellets reflected diet during that sampling period, we ignored pellets appearing old, bleached, or fallen apart, similar to Weiser & Powell (2010). Adult gulls occasionally regurgitate a mass of food (sometimes partially digested) in reaction to disturbance. These regurgitations were opportunistically collected during the incubation periods.

To characterize chick diet, regurgitated food samples were collected from chicks during early chick-rearing (approximately two weeks of age; Mandarte: 22 July 2009 and 24–26 July 2010; Cleland: 5 August 2010) and late chick-rearing (approximately four weeks of age; Mandarte: 11 August 2009 and 14–16 August 2010, Cleland: 26 August 2010) stages, based on our knowledge of mean laying or hatching dates for the colonies. Chicks were captured by hand (chicks are usually incapable of flight until 37–53 d of age; Vermeer 1963) and, to avoid sampling multiple chicks fed by the same parents, only one chick was sampled every few metres (Vermeer 1963, BC Conservation Data Centre 2011).

Laboratory analysis

Pellets and regurgitations were weighed and prey items were identified to the lowest possible taxonomic level using a dissecting microscope and local marine invertebrate and fish guides (Lamb & Edgell 1986, Kozloff 1987, Harbo 1999). Along with taxonomic ranking, samples were also scored for the presence/absence of items assigned to one of the following broad diet categories defined by Vermeer (1982): human refuse (e.g. poultry or pork meat/fat; human food items: pizza or sausage; garbage: piece of plastic bag, tinfoil), fish, marine invertebrate, terrestrial invertebrate (insects), digested animal matter (e.g. unidentifiable small terrestrial mammal), and plant matter. The frequency of occurrence (FOO) of each category was then calculated as a

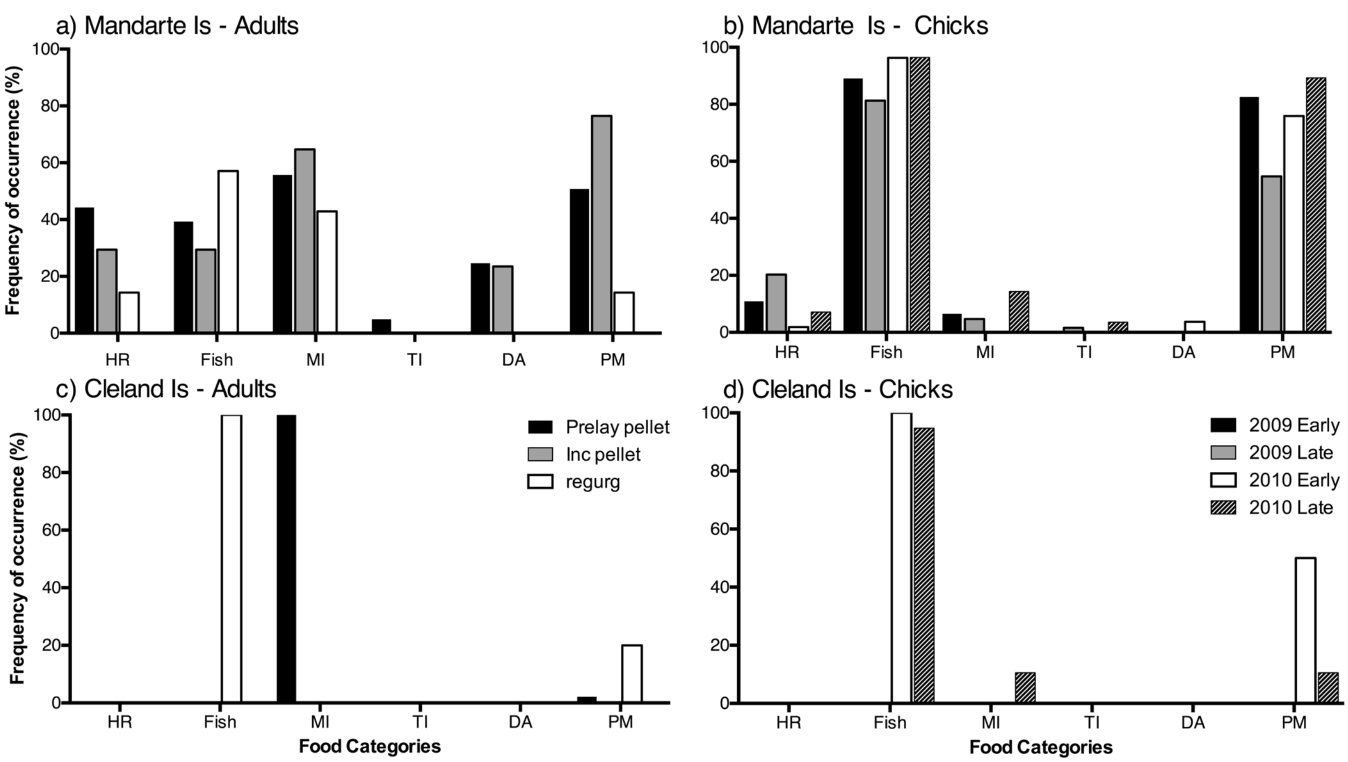

Fig. 1. Composition of Glaucous-winged Gull diet by breeding stage in adults and by year and date in chicks at Mandarte (top) and Cleland (bottom) islands. Data are expressed as frequency of occurrence (%) of six broad food categories: HR – human refuse, Fish – fish, MI – marine invertebrate, TI – terrestrial invertebrate, DA – digested animal matter, PM – plant matter.

measure of dietary composition. This indicates the percentage of total samples that contain a particular food category, or the presence/absence of that category, rather than quantity. FOO was chosen as the measure of interest to facilitate comparison of results with those obtained by Vermeer (1982).

Statistical analysis

Intra-colony and historical differences in diet were examined using a statistical method developed for multiple categorical choices (see Agresti & Liu 1999) in order to avoid violating the assumption of independence required to conduct Pearson's chi-squared tests. Data were broken down into multiple Pearson's chi-squared tests for each comparison using counts of presence/absence data (0 for absence, 1 for presence) and analyzed using JMP (version 8.0.2). An adjusted *P*-value was then calculated for each individual test using the Bonferroni method to account for multiple comparisons:

$$\tilde{p}_i = \min(cP_i,1)$$

where c is the number of food categories (or tests), and P_i is the *P*-value of the *i*th test. No difference was found between categories when $\tilde{p}_i \leq \alpha$ ($\alpha = 0.05$). To facilitate comparisons between diets of adults and chicks, and with historical results, we pooled adult pre-laying and incubation stages and early and late chick-rearing stages; however, these were not analyzed statistically, since pellets and regurgitations represent different sample types. Historical results from Henderson (1972) and Ward (1973) were used for comparisons, which were qualitative only, as dietary composition was not presented as FOO in these earlier studies.

TABLE 2
Comparison of composition of diet of adult and chick Glaucous-winged Gulls with historical data at Georgia Strait and west coast locations

	Frequency of occurrence (%)								
	Pellets from adults Pre-laying–Incubation				Regurgitations from chicks Early–Late				
	Georgia Strait		West Coast		Georgia Strait			West Coast	
Food categories	**1980[a] (n = 179)**	**2010 (n = 78)**	**1980[a] (n = 31)**	**2010 (n = 47)**	**1980[a] (n = 238)**	**2009 (n = 110)**	**2010 (n = 82)**	**1980[a] (n = 135)**	**2010 (n = 23)**
Human refuse	69.3	41.0	–	–	22.2	16.4	3.7	0.7	–
Fish	16.8	37.2	16.1	–	60.5	84.5	96.3	95.5	95.7
Marine invertebrates	[b]	57.7	[b]	100	[b]	5.5	4.9	[b]	8.7
Bivalves	23.5	[b]	12.9	[b]	11.3	[b]	[b]	1.5	[b]
Gastropods	0.6	[b]	6.5	[b]	0.4	[b]	[b]	–	[b]
Bivalve/gastropod	[b]	25.6	[b]	14.9	[b]	1.8	1.2	[b]	8.7
Chitons	2.8	2.6	–	–	0.4	–	–	–	–
Squid	–	–	–	–	–	–	–	1.5	–
Crabs	9.5	[b]	3.2	[b]	0.8	[b]	[b]	0.7	[b]
Shrimp	0.6	[b]	–	[b]	0.4	[b]	[b]	–	[b]
Crabs/Shrimp	[b]	29.5	[b]	4.3	[b]	1.8	2.4	[b]	–
Isopods	0.6	–	–	–	–	–	–	–	–
Euphausiids	–	–	–	–	–	0.9	–	–	–
Gooseneck barnacles	1.7	–	87.1	93.6	–	–	–	1.5	–
Errant polychaete	–	25.6	–	–	0.4	0.9	3.7	–	–
Sea star	1.7	1.3	–	2.1	5.0	2.7	–	–	–
Terrestrial invertebrates	3.0	3.8	–	–	0.4	–	1.2	–	–
Mice	0.6	–	3.2	–	–	–	–	0.7	–
Digested animal matter	0.6	24.4	–	–	11.8	0.9	2.4	4.4	–
Plant material	62.6	56.4	12.9	2.1	8.8	66.4	80.5	–	17.4

[a] Data from Vermeer (1982).
[b] Indicates a difference in the way diet categories were compiled between Vermeer (1982) and current data.

RESULTS

Adult and chick dietary ecology

Mandarte Island

Adults — Diet did not differ significantly between the pre-laying and incubation stages ($P > 0.059$ and $\tilde{p} > 0.356$ in all tests; Table 1, Fig. 1). Regurgitation contents from the incubation stage were generally consistent with the pellet data (Fig. 1). Fish in regurgitations was mostly too digested to identify, although Pacific Sand Lance *Ammodytes hexapterus* occurred in one.

Chicks — During both early and late chick-rearing stages in 2009 and 2010, chicks were fed mainly fish and plant matter, with a small fraction of regurgitations containing human refuse and marine invertebrates, and a few incidences of terrestrial invertebrates or digested animal matter (Table 1, Fig. 1). No significant differences were found in diet between early and late chick-rearing, with the exception of plant matter in 2009 ($\chi^2 = 9.347$, df = 1, $P = 0.0022$, $\tilde{p} = 0.0132$) and marine invertebrates in 2010 ($\chi^2 = 8.110$, df = 1, $P = 0.0044$, $\tilde{p} = 0.0264$). Occurrences of various fish species were similar between early and late chick-rearing stages within different years (Table 1).

Cleland Island

Adults — During the pre-laying period, 100% of the pellets contained marine invertebrates (Table 1). No pellets were found for the incubation period at Cleland Island despite our survey for them, precluding a comparison between the adult breeding stages. Regurgitations consisted solely of fish, which were almost exclusively Pacific Sand Lance (Fig. 1).

Chicks — There were no significant differences between the early and late chick-rearing stages ($P > 0.0583$ and $\tilde{p} > 0.1749$ in all tests). Regurgitations from both stages contained a high occurrence of fish, with late chick-rearing samples containing a greater occurrence of Pacific Herring *Clupea pallasi* but similar occurrence of Pacific Sand Lance (Table 1, Fig. 1).

Intra-colony dietary variation

Mandarte Island

Adult pre-hatch diet (pre-laying and incubation stages combined) had a higher percentage occurrence of human refuse, digested animal matter and marine invertebrate items, and lower frequency of fish and plant matter, than chick diets (Table 2). Adult regurgitations collected during the adult incubation stage also reflect this trend (Fig. 1).

Cleland Island

Diet assessed from adult pre-egg laying samples (no pellet samples were collected during adult incubation stage) differed considerably from chick samples, with adult samples having lower percentage occurrences of fish and higher marine invertebrate (Table 2).

Inter-colony dietary variation

Adults — While marine prey commonly occurred, diet at Mandarte Island (located in the Salish Sea) was much more variable than at Cleland Island (located on the west coast of Vancouver Island; Table 2). At Cleland Island, diet was almost exclusively marine (Table 2), and no human refuse was found in diet samples or observed at the colony.

TABLE 3
Fish species found in Glaucous-winged Gull chick regurgitations for each location and year sampled

Fish	Frequency of occurrence (%)				
	Georgia Strait			West Coast	
	1980[a] (n = 144)	2009[b] (n = 93)	2010[b] (n = 79)	1980[c] (n = 129)	2010[d] (n = 22)
Herring (*Clupea pallasi*)	55.6	9.7	2.5	24.8	22.7
Pacific sand lance (*Ammodytes hexapterus*)	1.4	25.8	53.2	21.7	50
Pacific saury (*Cololabis saira*)	–	–	–	20.2	–
Salmon (*Oncorhynchus* sp)	4.2	1.1	1.3	2.3	–
Pricklebacks/gunnels (suborder Zoarcoidei)	3.5	–	2.5	–	–
River lamprey (*Lampetra ayresi*)	1.4	–	–	–	–
Midshipman (*Porichthys notatus*)	–	1.1	–	–	4.5
Sculpin (Superfamily Cottoidea)	2.1	–	–	–	–
Unidentified and digested	43.1	64.5	43.1	34.9	31.8

[a] Data pooled from Mandarte, Mitlenatch, Snake, and Christie Islands and the Tsawwassen breakwater, Georgia Strait (Vermeer 1982).
[b] Mandarte Island.
[c] Data pooled from Triangle and Florencia Islands and Starlight Reef, west coast Vancouver Island (Vermeer 1982).
[d] Cleland Island.

Chicks — Chicks were fed primarily fish and plant matter at both colonies (Table 2). Although fish occurrence was similar between colonies, the occurrence of specific fish taxa differed (Table 3).

Historical dietary variation

Vermeer's (1982) data were obtained from multiple colonies at two locations: Georgia Strait/Salish Sea (5 colonies) and the west coast of Vancouver Island (3 colonies), but he presented pooled results for each location owing to a low number of intra-regional differences (his Table 1). This allowed us to make spatial comparisons with our sampled colonies in similar locations.

Georgia Strait/Salish Sea

Adults — There was a significantly lower percentage occurrence of human refuse in 2010 than in 1980 ($\chi^2 = 18.172$, df = 1, $P < 0.0001$, $\tilde{p} = 0.0006$), and a significantly higher percentage occurrence of fish ($\chi^2 = 12.807$, df = 1, $P = 0.0003$, $\tilde{p} = 0.0018$; Table 2) and digested animal matter ($\chi^2 = 42.881$, df = 1, $P < 0.0001$, $\tilde{p} = 0.0006$; Table 2). The format of Vermeer's (1982) data does not allow for a detailed comparison of marine invertebrate occurrence.

Chicks — Fish was the primary component of diet across all years; however, the occurrence of fish was significantly higher in 2010 than in the 1980 and 2009 samples ($\chi^2 = 14.134$, df = 1, $P = 0.0002$, $\tilde{p} = 0.0012$; and; $\chi^2 = 7.005$, df = 1, $P = 0.0081$, $\tilde{p} = 0.0486$; Table 2). In contrast, the occurrence of human refuse was significantly lower in 2010 than in both 1980 and 2009 ($\chi^2 = 14.630$, df = 1, $P < 0.0001$, $\tilde{p} = 0.0006$; and $\chi^2 = 7.785$, df = 1, $P = 0.0053$, $\tilde{p} = 0.0318$). Composition of fish shifted from a herring-dominant diet in 1980 to a Pacific Sand Lance-dominated diet in 2009 and 2010 (Table 3). Plant matter was also significantly more common in recent years than 1980 (2009 $\chi^2 = 126.336$, df = 1, $P < 0.0001$, $\tilde{p} = 0.006$; and 2010 $\chi^2 = 158.224$, df = 1, $P < 0.0001$, $\tilde{p} = 0.0006$). The format of Vermeer's (1982) data does not allow for a detailed comparison of marine invertebrate occurrence.

West Coast of Vancouver Island

Adults — The presence of fish in the diet was significantly less common in 2010 than 1980 ($\chi^2 = 8.100$, df = 1, $P = 0.0044$, $\tilde{p} = 0.0264$). As with the Georgia Strait, direct comparison of a broad marine invertebrates category is not possible (Table 2).

Chicks — No significant differences were found in percentage occurrence of the main diet categories, with the exception of plant matter ($\chi^2 = 24.008$, df = 1, $P < 0.0001$, $\tilde{p} = 0.0006$; Table 2). Total fish consumption occurred at similar frequencies in 1980 and 2010; however, higher occurrences of Pacific Sand Lance and Pacific Saury *Cololabis saira* were found in 2010 (Table 3).

DISCUSSION

Trophic level and proportion of marine prey significantly influence the concentrations of persistent organic pollutants accumulating in avian species (Jarman *et al.* 1996, Hebert *et al.* 2000, Elliott *et al.* 2009); thus, knowledge of female Glaucous-winged Gull dietary ecology before, and during, egg production are critical for interpreting contaminant deposition in eggs. Glaucous-winged Gulls in the Canadian Pacific region are considered local migrants, overwintering locally and arriving at the breeding colonies approximately a month in advance of egg laying (Vermeer 1963, Hatch *et al.* 2011, Elliott unpublished data). Therefore, resources allocated to egg production should reflect adult female diet and contaminants acquired within the region. In this study, we examined spatio-temporal variation in the diet of the Glaucous-winged Gull, in order to assess its utility as a marine contaminant monitoring species on the Pacific coast of Canada. We documented several sources of variation in diet that should be considered when interpreting various types of contaminants monitoring data. First, at each colony, and within each year, there was little short-term temporal variation in dietary ecology either in adults (comparing pre-egg laying and incubation-stage diets), or in chicks (comparing early versus late chick-rearing stages). In contrast, within each colony, adult pre-hatching diet and chick diet differed greatly. Third, at both colonies, adult pre-hatching diet was predominantly marine, but it was much more diverse closer to urban development. Last, diets at both colonies differed from documented historical diets.

Adult and chick dietary ecology

We found only minor short-term temporal variation in diet, both in adults between pre-laying and incubation stages (Mandarte Island), and in chicks between chick-rearing stages (Mandarte and Cleland Islands). Our results are consistent with those of Ramos *et al.* (2009), who found only minor variation in chick diet composition with age in Yellow-legged Gulls *L. michahellis* breeding on the Mediterranean coast of Spain. However, our results are contrary to those of Nogales *et al.* (1995), who reported that Herring Gull chick diet in southwest Scotland varies considerably between chick age classes, with a significant decrease in fish and increase in human refuse (chiefly poultry and pork) with age. Both studies were conducted in European ecosystems where human influence has significantly altered food web dynamics, and fish were acquired as offal (fish scraps) from commercial fishery vessels and fish packing plants rather than directly foraged from the marine environment. Variation in diet with chick age was also observed at Mandarte Island in the early 1970s, with a decrease in occurrence of fish and an increase in garbage and intertidal prey as chicks aged (Henderson 1972). In our study, a slight, non-significant increase in human refuse and a decrease in fish in diet were observed between the two chick-rearing stages in 2009, while no similar shift was observed in 2010.

Intra-colony dietary variation

At both colonies, adult pre-hatching and chick diet differed considerably in 2010, with chick diets having a much higher occurrence of fish. At Mandarte Island pre-hatching adults consumed a mixture of marine invertebrates, human refuse and fish, but provisioned chicks predominantly consumed fish. We acknowledge that conclusions on dietary differences based on separate sampling techniques (pellets versus regurgitations) should be tentative, as suggested by Ewins *et al.* (1994). While this disparity in diet composition may reflect a seasonal change in prey availability, research on both Western *L. occidentalis* and Herring Gulls concluded that a switch between pre-hatching and provisioning adult diet was likely triggered by nutritional requirements of their nestlings rather than seasonal increases in fish abundance (Pierotti & Annett 1987, Annett & Pierotti 1989). We are unable to make inferences about provisioning adult diet during the chick-rearing stages, since some seabird studies have revealed that provisioning adults may feed themselves different prey from the prey fed to their nestlings (Hodum & Hobson 2000, Davies *et al.* 2009).

Diet at the more remote Cleland Island colony also differed between pre-hatching adults and provisioned chicks in 2010, with adults consuming primarily marine invertebrates while chicks were fed almost an exclusively fish-based diet. Similar to our findings, Henderson (1972) documented the consumption of Goose-neck Barnacles *Pollicipes polymerus* during the adult pre-laying period at Cleland Island; however, a switch to a diet completely dominated by Pacific Sand Lance was noted in incubating adults. Adult Kelp *L. dominicanus* and Herring Gulls have been found to switch their diet from marine invertebrate-dominated during pre-egg laying and incubation stages to fish after nestlings hatch (Spaans 1971, Pierotti & Annett 1987, Bertellotti & Yorio 1999). While this seems likely, we did not sample provisioning adults and cannot make a direct comparison. The consumption of marine invertebrates before egg laying is thought to provide gulls with the resources necessary for egg formation and leads to a more rapid recovery from egg-laying stress and an increased hatching/fledging success (Pierotti & Annett 1987, 1991).

Inter-colony dietary variation

Adult pre-hatching diet differed markedly between the colonies, with adults at Mandarte Island incorporating both natural marine prey and human refuse, and Cleland adults foraging almost exclusively on marine prey. Offal appears to be the only diet item that may indicate human influence at Cleland Island. As in other Glaucous-winged Gull studies (Vermeer 1992) and findings in the closely-related Herring Gull (Fox *et al.* 1990), this study found that adults at both colonies foraged in an opportunistic manner, with diet reflecting locally abundant items and the association of colonies with urban areas. In contrast, few spatial differences were observed in the occurrence of broad diet categories in chicks, aside from human refuse, which had a low occurrence at Mandarte Island but was absent at Cleland. The importance of forage fish during the chick-rearing stage was clearly exhibited at both colonies.

Historical dietary variation

The prevalence of human refuse in the diet of Mandarte Island Glaucous-winged Gulls is lower than results reported from historical studies conducted 30–40 years ago (Henderson 1972, Ward 1973, Vermeer 1982). Although our data are based on only a single year for comparison, and interannual variation in gull diets of the Pacific coast can be substantial (Ainley *et al*. 1990), results for refuse consumption among historical diet studies were consistent over a 10-year period, indicating that a change in pattern between 1980 and 2010 is plausible. Following Vermeer's study (1982), total abundance of Pacific Herring in the Georgia Strait rose to peak levels in 2003 and subsequently declined, leaving herring less available to foraging gulls at the time of our study (Therriault *et al.* 2009). While no clear explanation exists, it is possible that the abundance of Pacific Sand Lance, another key forage fish species for many seabird species in Pacific waters, increased during this time and compensated for the scarcity of herring. Although very little is known about sand lance abundance and distribution in the Strait of Georgia (Therriault *et al.* 2009), data from chick diet indicate that sand lance occurrence was elevated compared with 1980. Another possible contributing factor is the decline of the Georgia Basin Glaucous-winged Gull population between the 1980s and 2010 (Blight *et al.* 2015), easing the foraging pressure on available marine prey.

In keeping with historical findings (Henderson 1972, Ward 1973, Vermeer 1982), chicks at Mandarte Island were provisioned primarily with fish. In contrast, chick diets contained a lower occurrence of human refuse than reported by Vermeer (1982); however, considerable inter-annual variation exists between our sampling years (2009 and 2010). The short-term fluctuation in the occurrence of forage fish prey could be the result of climatic variation (e.g. El Niño-Southern Oscillation [ENSO]; see Ainley & Boekelheide 1990 for ENSO effect on Western Gull diet). Availability of marine prey may fluctuate at various temporal scales, leading to a corresponding increase in reliance on anthropogenic and terrestrial food items. The gulls at Mandarte Island demonstrated the ability to switch prey types during times of lower marine prey abundance; however, lower proportions of fish in the diet of gulls has previously been associated with lowered reproductive success (Murphy *et al. 1984*, Pierotti & Annett 1987, Fox *et al.* 1990). When comparing reproductive success between Cleland and Mandarte Islands, Ward (1973) determined that fledging success was higher at Cleland, where chicks were provisioned with more natural marine prey (primarily sand lance and herring) and no human refuse. Similarly, nestling consumption of lower proportions of fish at Mandarte in 2009 may be responsible for the significantly lower fledging success that year (Louise Blight pers. comm.).

Adults in our study appear to have consumed less fish than reported by Vermeer (1982) for west coast colonies; however, an absence of adult samples from the incubation period renders this comparison incomplete. Results from chick stages do not indicate any temporal dietary differences when compared with Vermeer (1982), with the exception of plant matter, which may have been an artifact of sampling. The overall occurrence of fish remains equivalent between years, although late-stage chicks in 2010 were provisioned with a higher percentage of Pacific Sand Lance and a lower percentage of Pacific Saury than 1982 (Vermeer 1982). When compared with historical findings, diet on Cleland Island appears to have remained unaffected by human influences such as urbanization and commercial fishing pressures in the last 30 to 40 years. This reflects conclusions from Chen *et al.* (2012), who found a neighbouring colony, Florencia Island, to have had the lowest levels of flame retardant compounds across all CMP sites.

Conclusions and applications to contaminant monitoring

This assessment of diet in Glaucous-winged Gulls confirms that they are generalists, foraging primarily on natural marine prey while opportunistically supplementing their diets with anthropogenic and terrestrial items. Our results support the use of the Glaucous-winged Gull egg as a medium for monitoring marine contaminants on the west coast of Vancouver Island; however, some caution should be extended to the interpretation of contaminant results from colonies close to urban locations, as we found that adult gulls foraged on a mix of dietary sources and relied heavily on anthropogenic sources in some years. We recommend further monitoring be paired with stable isotope analysis to incorporate an assimilated dietary signature and reflect year-to-year baseline fluctuations.

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