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BEHAVIOR AND NUMBERS OF MARBLED MURRELETS MEASURED WITH RADAR

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Abstract.—I used high-frequency surveillance radar to estimate the numbers of Marbled Murrelets (*Brachyramphus marmoratus*) entering two watersheds on Vancouver Island, British Columbia. An accurate census was possible where incoming birds were funnelled through a narrow inlet (Bedwell-Ursus watershed), but counts were less reliable on more open coastline (Carmanah Valley). An estimated minimum of 900 and 100 murrelets, respectively, entered these watersheds at dawn in June 1995. Radar yielded 5–10 times more detections than human observers using the audio-visual Pacific Seabird Group (PSG) protocol. Radar revealed a concentrated influx of murrelets 35–60 min before sunrise, but the audio-visual surveys failed to detect this peak. Most audio-visual detections occurred later, from 35 min before to 90 min after sunrise, when the radar showed intensive circling and departure behavior. This implies that audio-visual surveys underestimate the number of active nesters and sample many murrelets that might be performing aerial displays rather than commuting to nests. The radar revealed considerable activity at dusk (43% and 29% of dawn detection rates at Carmanah and Bedwell, respectively), a period not normally sampled in the PSG protocol. Birds leaving the forest for the ocean flew faster (mean 119 km/h) than incoming birds (74 km/h) or those circling over the forest (81 km/h).

MEDICIÓN DE LA CONDUCTA Y LOS NÚMEROS DE *BRACHYRAMPHUS MARMORATUS* CON UN RADAR.

Sinopsis.—Utilicé un radar de monitoreos de alta frecuencia para estimar el número de *Brachyramphus marmoratus* entrando a dos vertientes en la Isla de Vancouver, British Columbia. Se pudo hacer un censo preciso al canalizar las aves entrantes a través de una entrada estrecha (vertiente de Bedwell-Ursus), pero los conteos fueron menos confiables en costas más abiertas (Valle de Carmanah). Minimos estimados de 900 y 100 aves, respectivamente, entraron a estas vertientes al amanecer de Junio 1995. El radar produjo 5–10 veces más detecciones que los observadores humanos usando el protocolo audiovisual del Grupo de Aves Marinas del Pacifico (PSG). El radar reveló un influjo concentrado de aves 35–60 minutos antes del amanecer, pero los censos audiovisuales fallaron en detectar este aumento. La mayoría de las detecciones audiovisuales ocurrieron más tarde, de 35 minutos antes hasta 90 minutos después del amanecer, cuando el radar indicó intensidad de vuelos circulares y comportamiento de salida. Esto implica que los monitoreos audiovisuales subestiman el número de anidantes activos y muestrean muchas aves que pueden estar llevando a cabo exhibiciones aereas más que viajando a los nidos. El radar reveló actividad considerable al anochecer (43% y 29% de las detecciones de amanecer en Carmanah y Bedwell, respectivamente), un período no comúnmente muestreado en el protocolo del PSG. Aves dejando el bosque hacia el océano volaron más rápido (promedio de 119 km/h) que aves que llegaban (74 km/h) o aquellas que volaban en círculos sobre el bosque (81 km/h).

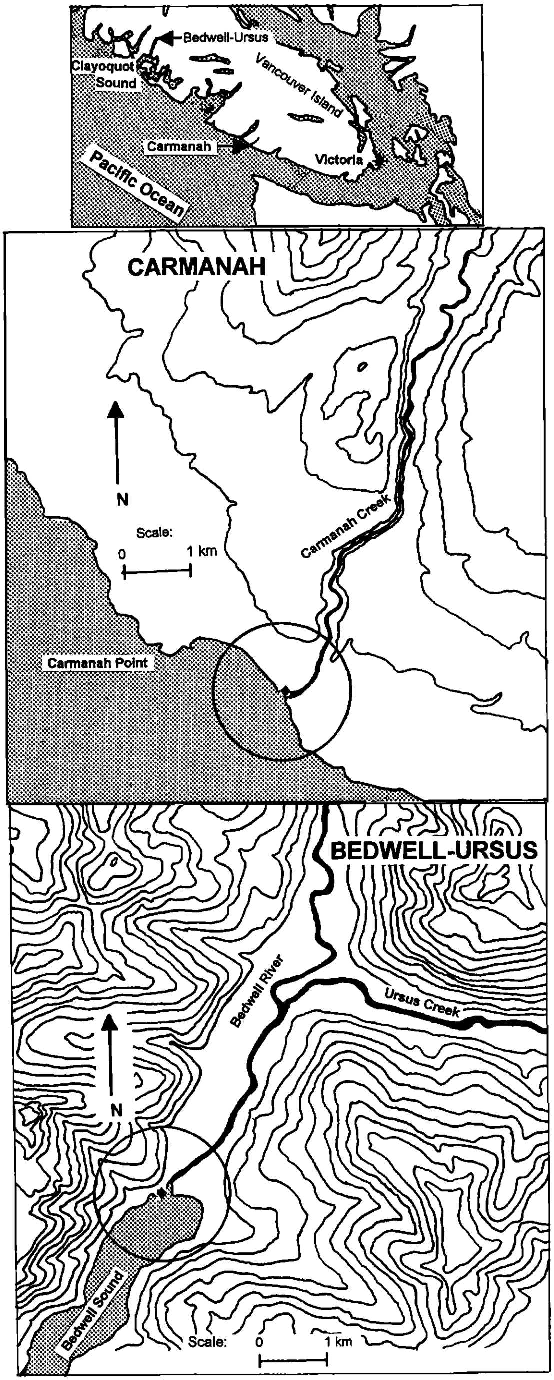
The Marbled Murrelet (*Brachyramphus marmoratus*) is a small alcid that uses large old-growth and mature conifers as nest sites through much of its range (Carter and Morrison 1992, Nelson and Sealy 1995, Ralph et al. 1995). Nesting birds visit nests quietly in dawn and dusk twilight (Nelson and Hamer 1995, Singer et al. 1991). Nests are usually widely scattered, cryptic, and hard to find (Nelson and Hamer 1995), making it difficult to census the breeding population and study their nesting behavior and habitats. Consequently, a protocol has been developed by the Pacific Seabird Group (PSG) for studying behavior and determining presence and probable nesting, on the basis of auditory and visual detections of murrelets made by observers on the ground (Paton 1995, Ralph et al. 1994). Detection rates are used to quantify murrelet activity levels at inland sites (Paton 1995) and to determine the effects of seasons, weather, topography, and vegetation on the birds (Hamer 1995, Kuletz et al. 1995, O'Donnell et al. 1995, Rodway et al. 1993a,b). Although this protocol is used throughout the bird's range in North America (Alaska through central California), it samples only a fraction of the murrelets active in the area (Hamer et al. 1995) and does not directly address all aspects of censusing or behavior. Specifically, the protocol does not allow estimates of actual numbers of birds entering a watershed or visiting a forest stand (Paton 1995). It is also not known whether audio-visual detections accurately reflect the timing of behavior patterns at dawn and dusk.

Pilot studies showed that Marbled Murrelets could be detected with radar at ranges up to 1.3 km and distinguished from most other birds found in the same habitats (Burger and Dechesne 1994, Hamer et al. 1995). Human observers seldom detected murrelets at distances greater than 300–350 m (Hamer et al. 1995), and in most forest habitats observers were likely to see murrelets within 100 m and hear them within 300 m (Ralph et al. 1994). As a result, experienced ground observers detected only 55% of the murrelets recorded on radar (Hamer et al. 1995). The major limitations of radar are the restrictions of the scanning area caused by reflections from trees and hills and the inability to detect murrelets flying below or within the forest canopy. Radar is useful in open, shallow valleys or flat country, but this topography is rare in much of the murrelet's range, and even in such habitat some low-flying murrelets are missed (Hamer et al. 1995).

In this study I mounted a radar at the mouths of two drainages, in situations that offered large expanses of open sky at the coast. My goals were to test the efficacy of radar in such locations, estimate the total number of murrelets entering forested watersheds from the ocean, observe the diurnal chronology of flight behaviors, compare audio-visual detection rates with those made with radar, and measure flight speeds.

METHODS

Radar was deployed at the mouths of two drainages on southwestern Vancouver Island (Fig. 1): Carmanah Creek (48°36.5′N, 124°43.4′W) and Bedwell-Ursus (49°22.0′N, 125°46.5′W). Carmanah Creek is a permanent stream draining a 6600 ha valley, which is largely covered by old-growth conifers (>250-yr old) and is known to support nesting Marbled Murrelets (Burger 1995a, Jordan and Hughes 1995). The Bedwell River drains the 16,000 ha Bedwell Valley, which is largely covered by second-growth forest 20–80-yr old, and the 5000 ha Ursus Valley, which is unlogged and covered with old-growth coniferous forest. Densities of Marbled Murre-


Bedwell-Ursus
Clayoquot Sound
Vancouver Island
Carmanah
Victoria
Pacific Ocean
CARMANAH
N
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Carmanah Creek
Carmanah Point
BEDWELL-URSUS
Bedwell River
Ursus Creek
N
Bedwell Sound
Scale: 0 1 km

lets at sea adjacent to both study areas were among the highest in British Columbia (Burger 1995b, Sealy and Carter 1984). Radar and audio-visual observations were made at Carmanah and Bedwell-Ursus from 6–15 and 19–24 Jun. 1995, respectively.

Murrelets were tracked with a high-frequency marine surveillance radar (Furuno FR810D, 9410 MHz, 10 KW, with a 2.0 m antenna) powered by a 12 V deep-cycle battery. The antenna was mounted on a platform 2.5 m above ground, and modified according to Cooper et al. (1991). The antenna beam was tilted slightly upwards to scan a 25° vertical segment above the horizon and an adjustable aluminum anti-clutter screen was mounted on the beam's lower edge. Both the rain- and sea-scatter suppressors were turned off and the gain was set near full strength to give maximum sensitivity to the signals. The scanning radius was 1.0 km. Speed of the murrelets was estimated from the distance covered between successive images on the screen (measured with a ruler with a precision equivalent to 10 m) divided by the time taken for the antenna to make a complete horizontal revolution (3.0 s).

Radar images of Marbled Murrelets were distinguished from those of other birds or bats by their size (bats and smaller birds produce small images), speed (see below), and flight path (most murrelets could be tracked in flights from the ocean into the forest, which few other birds would do). All the radar identifications were made by the author, who had >50 h experience tracking murrelets (Burger and Dechesne 1994) and other species of birds. Detections were classified as incoming or outgoing (direct flight from ocean to forest, and *vice versa,* respectively) and circling over the forest (with a flight path that curved and was not obviously heading into or out of the forest). The few detections of birds circling over the water were ignored.

Hamer et al. (1995) found that misidentifications of Marbled Murrelets on radar screens were more likely at coastal sites, due to confusion with shorebirds and other fast-flying species. Their radar technician correctly identified 88% of murrelet targets at coastal sites and 98% inland. There were no shorebirds present at my study sites. Gulls (*Larus glaucescens* and *L. canus*) and Bald Eagles (*Haliaeetus leucocephalus*), which were present in small numbers at both sites, could be distinguished by their slow flight. Band-tailed Pigeons (*Columba fasciata*) and mergansers (*Mergus* spp.) have similar flight speeds to murrelets (Hamer et al. 1995). Pigeons were rare at both sites and, unlike murrelets, generally flew in flocks of five or more birds. Twelve Common Mergansers (*Mergus merganser*) were resident at the Bedwell estuary, but did not follow the same flight

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FIGURE 1. Location of radar tracking stations at the mouths of Carmanah Creek and the Bedwell River on the west coast of Vancouver Island. The circles show the areas (1 km radius) scanned by the radar. Elevation contour lines are in 100 m intervals. The inset shows the locations of the two sites on Vancouver Island.

paths as murrelets and would not have significantly affected the estimate of murrelet numbers even if a few were misidentified as murrelets.

Ground-based observers recorded visual and audio detections of Marbled Murrelets following the Pacific Seabird Group (PSG) protocol (Ralph et al. 1994). An observer was stationed within 10 m of the radar antenna with each radar survey. Audio-visual surveys were also made within the week encompassing each set of radar surveys at inland stations (four stations in mid-valley, 6–9 km inland, and two in the upper-valley, 18–20 km inland, at Carmanah; eight stations in the Bedwell, 2–4 km inland, and 11 stations in the Ursus, 5–12 km inland). In the PSG protocol the unit of murrelet activity is the detection, defined as the sighting or hearing of one or more murrelets acting in a similar manner (Paton 1995, Ralph et al. 1994). Detections and other observations were recorded on tape recorders and later transcribed. All observers had been trained in the PSG protocol and had completed 12 or more surveys prior to this study.

In accordance with the PSG protocol at these latitudes (Ralph et al. 1994, Rodway et al. 1993a), audio-visual surveys began 60 min before official sunrise, and ended 60 min after sunrise, or 20 min after the last detection. Radar tracking and audio-visual surveys at the radar station were started 90 min before sunrise, after pilot surveys showed that many murrelets were active before the protocol's recommended starting time, and before it was light enough to see flying murrelets. At dusk, radar and audio-visual surveys began 40 min before sunset and sampled a minimum of 2 h. Times of sunrise and sunset for Carmanah and Bedwell were obtained from the Dominion Astrophysical Observatory, Saanich, British Columbia.

Cloud cover, precipitation, and illumination are known to affect the timing and duration of flight activities of Marbled Murrelets; dawn flights are sometimes delayed and prolonged in cloudy or foggy conditions (Nelson and Peck 1995, Rodway et al. 1993a). Heavy rain also obscures radar images. Weather conditions were relatively uniform during each study period: 90–100% cloud with occasional showers at Carmanah, and 100% coastal fog cover with no precipitation at Bedwell-Ursus. Data from incomplete radar surveys (more than 10 min of rain) at Carmanah were not used for estimating numbers or analysis of timing, but were included in analyses of flight speed and flock size. It required one or two radar surveys to become familiar with the radar landscape and the birds' flight paths. Consequently, I discarded the first dawn and dusk survey at each site, except that the first dawn survey at Bedwell was analysed for chronology.

RESULTS

Detection frequency, behavior, flock size, and spatial patterns.—The number of radar detections at Carmanah and Bedwell ranged from 84–146 and 558–1065, respectively, at dawn (Fig. 2) and 48–52 and 213–288, respectively, at dusk (Fig. 3). Incoming birds, which approached over the

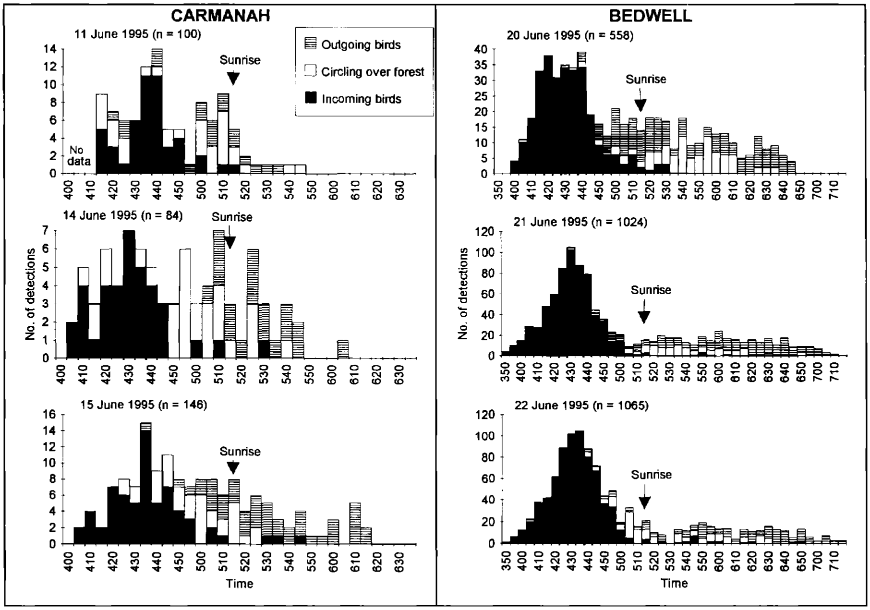

FIGURE 2. Frequency distributions of radar detections of Marbled Murrelets at Carmanah and Bedwell at dawn, plotted in 5 min intervals, starting at 0400 at Carmanah and 0350 at Bedwell. The sample sizes are the numbers of detections.

ocean, were detected more frequently than circling or outgoing birds, whose flight over the forest was sometimes masked by hills, trees, and ground clutter. Consequently, estimates of numbers and mapping of flight paths focused on incoming birds.

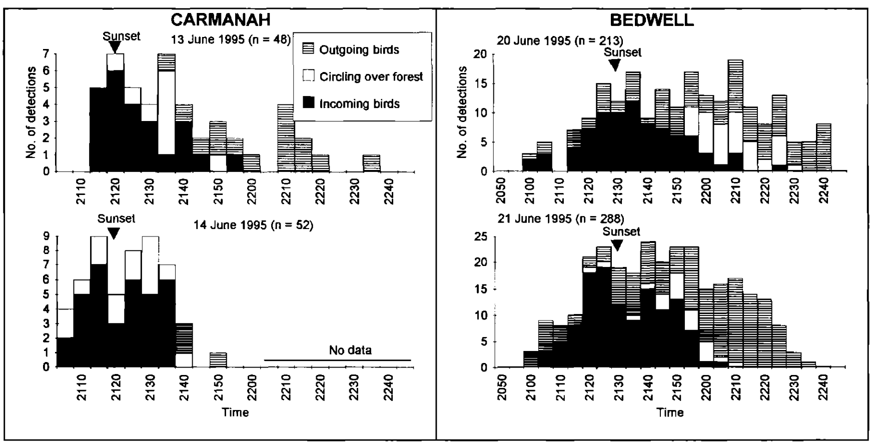

FIGURE 3. Frequency distributions of radar detections at Carmanah and Bedwell at dusk. Codes as in Figure 2.

TABLE 1. Flock size of Marbled Murrelets detected by radar and visually by ground observers at the Carmanah and Bedwell-Ursus study areas during dawn and dusk surveys.

Time	Area and detection type	% of detections		No. of detections	Significance[b]	
		1 bird	>1 bird		χ^2	*P*
DAWN SURVEYS						
	A. Carmanah					
	Radar detections					
	Incoming birds	66	34	180	4.877	>0.05
	Circling over forest	77	23	129		
	Outgoing birds	75	25	107		
	Total	72	28	416		
	Visual detections[a]	66	35	365	3.429	>0.05
	B. Bedwell-Ursus					
	Radar detections					
	Incoming birds	68	32	1672	282	<0.001
	Circling over forest	20	80	366		
	Outgoing birds	62	38	609		
	Total	60	40	2647		
	Visual detections[a]	41	59	358	46.3	<0.001
DUSK SURVEYS						
	A. Carmanah					
	Radar detections					
	Incoming birds	57	43	58	2.292	>0.05
	Circling over forest	67	33	24		
	Outgoing birds	75	25	20		
	Total	63	37	102		
	Visual detections[a]	94	6	130	34.779	<0.001
	B. Bedwell-Ursus					
	Radar detections					
	Incoming birds	60	40	205	44.902	<0.001
	Circling over forest	18	82	61		
	Outgoing birds	65	35	235		
	Total	57	43	501		
	Visual detections[a]	95	5	19	10.587	<0.001

[a] Flock size breakdown: Carmanah at dawn: 30.1% two birds, 4.1% three, and 0.3% four; Bedwell-Ursus at dawn: 46.1% two, 8.9% three, 3.4% four and 0.8% six; Carmanah evening: 5.4% two and 0.8% three; Bedwell-Ursus evening: 5.3% two birds.

[b] χ^2-tests assess differences in flock size among behaviors (for radar detections) and between visual and radar detections (for visual detections).

Discrimination of flock size was difficult on the radar screen unless 4–5 successive images could be seen. Flocks of two or more murrelets made up 28% and 40% of the dawn radar detections at Carmanah and Bedwell, respectively, and 37% and 43% of the dusk detections, respectively (Table 1), but a few of the images recorded as single birds might have been two or more flying close together. Flocks of 3–5 birds were sometimes noted, but individuals could not be reliably counted. Compared to visual detections, the proportion of radar detections in flocks of >1 bird was similar at dawn in Carmanah, significantly lower at dawn in Bedwell-Ursus but significantly higher in dusk surveys at both sites (Table 1). The proportion of flock detections was similar for the three behavior categories in both dawn and dusk surveys at Carmanah, but there were significantly more flocks among circling murrelets than other behaviors at dawn and dusk at Bedwell.

Flight speeds ranged from 40–158 km/h. Mean speeds (±SD) of incoming (74 ± 12 km/h, n = 132) and circling birds (81 ± 11 km/h, n = 22) did not differ significantly and were similar at the two study sites (two-tailed t-tests, $P > 0.05$ in each case). Speeds of outgoing birds at Carmanah (136 ± 17 km/h, n = 40) and Bedwell (106 ± 20 km/h, n = 51) differed significantly (t = 7.775, df = 89, $P < 0.001$) which seems to be related to topography. Birds at Carmanah were diving down from above tall trees on a raised coastal plain, whereas most of those leaving Bedwell were following a low-lying valley with shorter trees. At both sites the outgoing birds (overall mean speed 119 ± 24 km/h, n = 158) flew significantly faster than both incoming and circling birds (t-tests, $P < 0.001$ in each case).

The timing of flight activities varied little among the sample days at dawn (Fig. 2) and dusk (Fig. 3). At both times there was a concentrated pulse of incoming birds; at dawn this peaked 35–60 min before sunrise, but at dusk it coincided with sunset. Circling and outgoing birds were recorded over more prolonged periods, but were concentrated from 30 min before to 90 min after sunrise, and in the hour following sunset.

At Carmanah, birds entering and leaving the forest tended to avoid the creek mouth, and most crossed over the low coastal plain 200–700 m to the northwest (Fig. 4). The apparent decline in activity beyond 700 m was partly due to the reduced coastal area scanned by the radar at the edge of the scanning circle. Many birds appeared likely to enter the valley beyond the 1 km range of the radar. By contrast, murrelets entering the Bedwell Valley were funnelled through a narrow corridor over the estuary. Few flew near the high, steep slopes bordering the estuary, indicating that most of the incoming birds were detected.

Estimates of incoming murrelets.—Minimum estimates of incoming murrelets were calculated conservatively by assuming a flock size of two for all detections of >1 bird (Table 2). At dawn, at least 48–99 birds entered Carmanah and 878–989 entered Bedwell. Additional adults would have been incubating on the nests at this time, so the total breeding populations would have been somewhat higher. Fewer incoming birds were detected at dusk; the highest dusk count was 47% of the highest dawn count at Carmanah and 19% at Bedwell (Table 2).

Comparison of radar with standard audio-visual observations.—At dawn, the mean frequency of audio-visual detections recorded at the radar station was 22% of that of radar detections at Carmanah Valley and 10% at Bedwell (Fig. 5). At dusk, they were 6% and 13%, respectively. Similar results were obtained from audio-visual surveys made further inland in the week encompassing each radar survey (Fig. 5). There were insufficient data to test the day-to-day correlation between radar and audio-visual detection rates.

The timing of detections at dawn differed significantly between radar

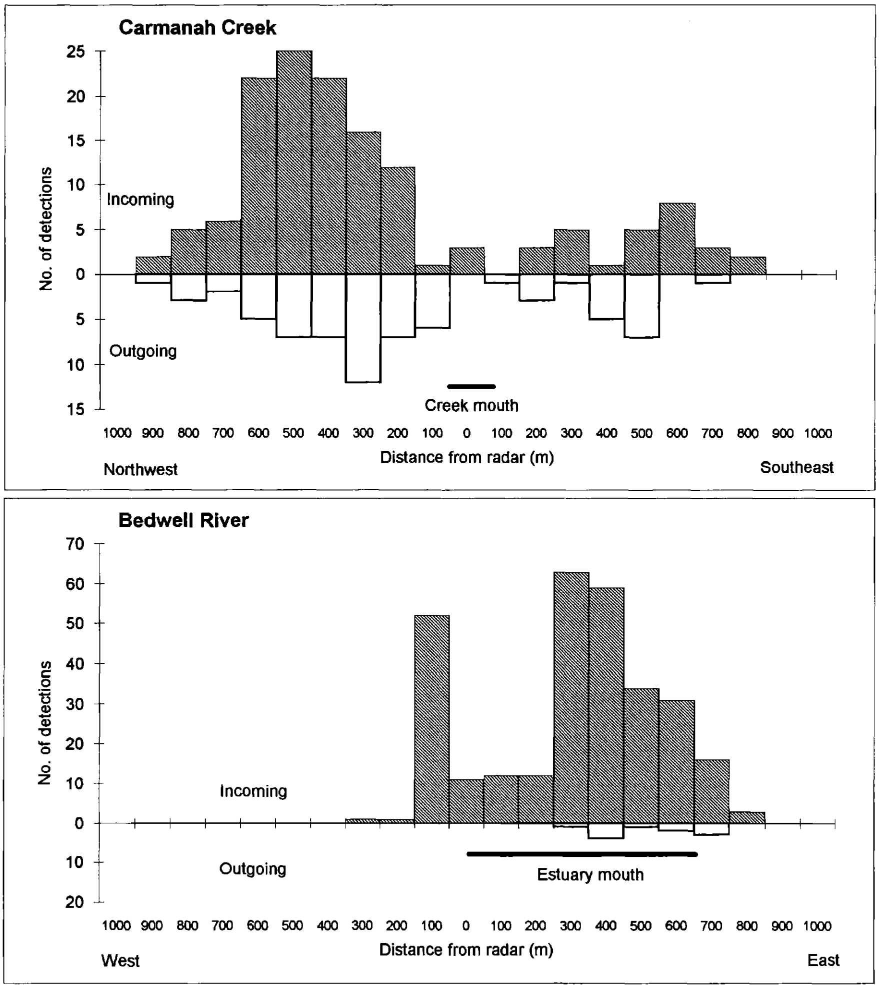

FIGURE 4. Spatial distributions of detections of Marbled Murrelets crossing the coastline at Carmanah and Bedwell, plotted in 100 m intervals on either side of the radar station. The thick horizontal lines indicate the locations of the creek and estuary. Distributions of outgoing birds were not sampled as intensively as those of incoming birds.

and audio-visual observations at both Carmanah and Bedwell-Ursus (Fig. 6; Kolmogorov-Smirnov test, $P < 0.01$ in each case). Most importantly, the audio-visual surveys failed to show the intense pre-sunrise peak of incoming murrelets, even when the audio-visual surveys began at the same time as the radar observations, which was earlier than recommended by the PSG protocol. Most of the audio-visual detections occurred from 35 min before to 90 min after sunrise, at the time when the radar was indicating mostly circling or outgoing behavior. Although the distribution pat-

TABLE 2. Minimum number of Marbled Murrelets entering the Carmanah and Bedwell valleys estimated from the numbers of incoming radar detections at dawn and dusk in June 1995.

			No. of incoming detections		No. of birds[a]		
			Flock size		Flock size		
Location	Time	Date	1	>1	1	>1	Total
Carmanah	Dawn	11 June	41	7	41	14	55
		14 June	26	11	26	22	48
		15 June	31	34	31	68	99
	Evening	13 June	12	12	12	24	36
		14 June	21	13	21	26	47
Bedwell	Dawn	21 June	410	244	410	488	898
		22 June	572	153	572	306	878
	Evening	20 June	46	37	46	74	120
		21 June	77	45	77	90	167

[a] A flock size of two was assumed for all radar detections of more than one bird.

terns of audio-visual detections varied among stations, those further in the interior showed no consistent delays in activity peaks indicating that flight time needed to reach inland sites did not significantly influence the timing of audio-visual detections.

There were insufficient audio-visual detections at dusk, to make statistical comparisons of timing with radar detections, but the divergence between the two methods seemed less than at dawn. Darkness prohibited visual detections 30–40 min after sunset, but calls were heard and birds still appeared on radar up to 80 minutes after sunset (Fig. 3).

DISCUSSION

Timing of breeding behavior and daily visits.—At the time of this study (6–24 June) most of the breeding Marbled Murrelets in our study area would have been in the latter half of the incubation period, or rearing small chicks (Hamer and Nelson 1995, Sealy 1974). An unknown proportion of failed breeders and non-breeders prospecting for nests or courting would also have been flying over the forest. The concentrated pre-sunrise peak of incoming flights seen with radar coincided with the time that most incubation exchanges and feeding visits might be expected at these latitudes (Nelson and Hamer 1995, Nelson and Peck 1995). Few incoming birds were recorded after the peak, and the majority of incoming active breeders would therefore be sampled in this pre-sunrise peak. The ability of radar to detect and count these birds makes it a valuable tool for estimating populations in watersheds, and for tracking seasonal and annual variations in breeding activity.

The radar also confirmed that there was a second, smaller peak of activity at dusk, which matched the timing of dusk visits recorded at murrelet nests elsewhere (Nelson and Hamer 1995, Nelson and Peck 1995).

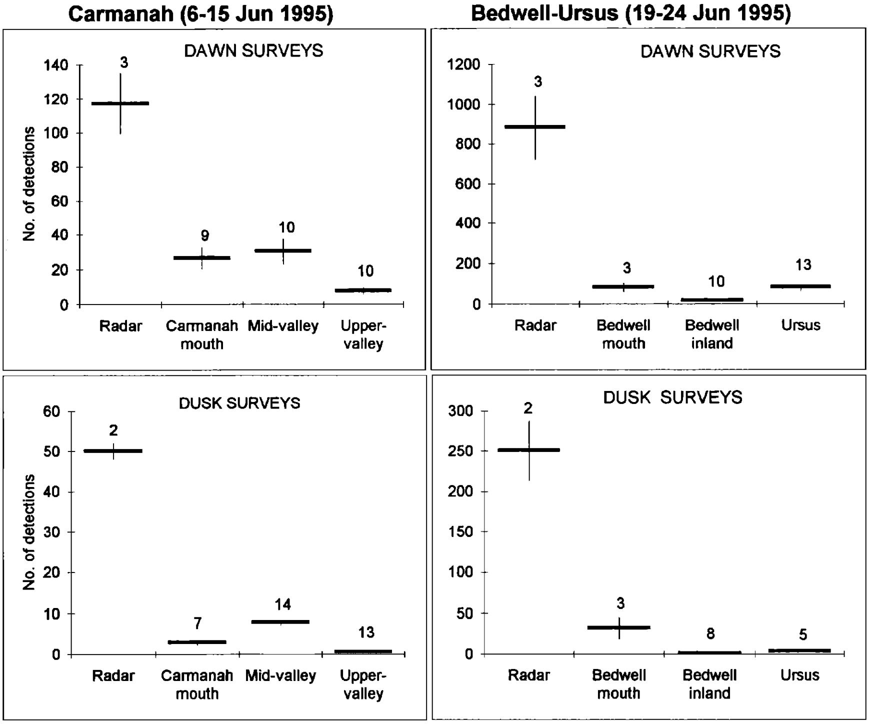

FIGURE 5. Comparison of the mean frequencies of radar detections at Carmanah and Bedwell with those of audio-visual detections made within 10 m of the radar stations (Carmanah and Bedwell mouths), and at inland stations during the week encompassing each radar sampling period. Means (± standard error) are shown, with the number of surveys.

There are no confirmed records of incubation exchanges at dusk (Nelson and Hamer 1995) although such exchanges might have occurred at a ground nest in Alaska (Simons 1980). Clearly, most information on breeding murrelets is likely to come from dawn surveys, but the inclusion of dusk surveys could provide an additional 30–40% of detections. This would enhance analyses of relative densities, breeding chronology, and habitat requirements, and provide additional opportunities to locate nests.

Radar as a census tool.—Radar counts of incoming birds appear to provide the most reliable and flexible method for estimating the number of Marbled Murrelets using a watershed. Audio-visual surveys, such as the PSG protocol, do not allow estimates of absolute bird numbers (Paton 1995, Ralph et al. 1994). Several detections could arise from a bird or flock repeatedly circling the observer, and the numerical relationship between detection frequency and number of birds is not known. Visual counts of murrelets entering or leaving watersheds are also likely to be

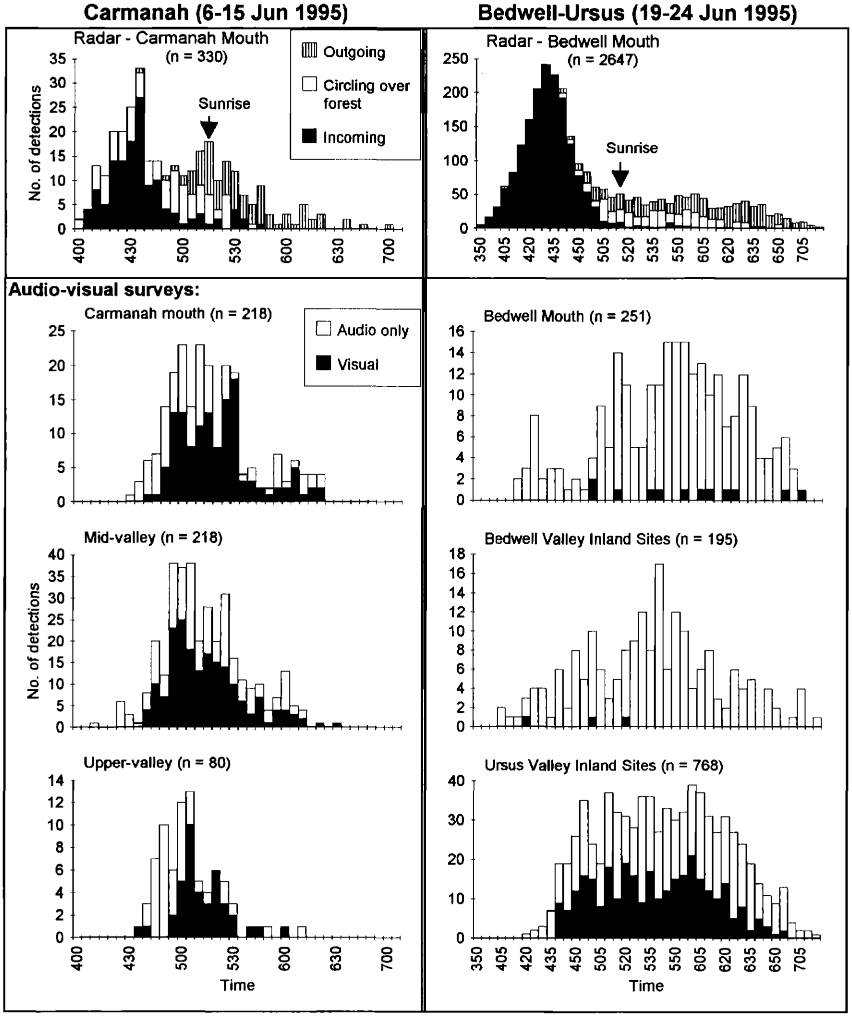

FIGURE 6. Comparison of the timing of radar detections (top graphs) with audio-visual detections in dawn surveys at Carmanah and Bedwell-Ursus. Surveys at Carmanah and Bedwell mouths were made within 10 m of the radar station. See text for locations of inland survey stations. Data were pooled from several days of observations within the time period shown and plotted in 5 min intervals. The sample sizes are numbers of detections.

unreliable. My study showed that observers at the coast detected only 6–22% of the murrelets flying past. The dark murrelets were difficult to detect against the trees and hillsides, even after sunrise, unless they passed directly overhead. Counts made from stationary boats anchored near the shore might allow improved visibility, but increase the risk of erroneous inclusion of circling birds or those coming from other watersheds. Prestash et al. (1992) used this method in Mussel Inlet, British Columbia, to estimate numbers exiting the adjacent watershed, but their tallies fluctuated widely from day to day. Even in broad daylight, the radar is far more likely than a human to detect a flying murrelet beyond 100–200 m. Radar operates well in foggy weather and misty drizzle, but neither radar nor visual observers provide reliable counts in heavy rain.

This study revealed some of the limitations of radar censusing. Several factors contribute to underestimates of total numbers. Some low flying birds might evade detection, but if birds were counted as they crossed the shore this could be minimized, because they would be flying in unobstructed skies, above or close to, tree height. Flocks larger than two birds are likely to be underestimated, and a few pairs might be mistaken for single birds. The calculation in Table 2 assumed all flocks had two birds, when both radar and visual observations indicated that some flocks were larger. Some birds might also be missed when many were in the radar field at the same time. Incubating birds and those skipping a nest visit would not be tallied, but the limited evidence suggests that most murrelets make one dawn incubation exchange and feed their chick at least once at dawn (Hamer and Nelson 1995). Numbers might be overestimated if a large proportion of adults made several round trips to the nest from the ocean. There are some records of individuals making more than one dawn visit to a nest (I. Manley pers. comm.) but most adults seem to make only a single visit at dawn and again at dusk (Nelson and Hamer 1995, Nelson and Peck 1995), and the compact peak of incoming birds seen on radar at both sites suggests that repeat visits were rare.

Radar censusing works best when the incoming murrelets are funnelled through a narrow inlet, such as at Bedwell. In my study, the minimum estimate of 900 murrelets entering the Bedwell-Ursus was more reliable than the estimate of 100 entering Carmanah. It was obvious at Carmanah that many murrelets crossed the coastline more than 1 km from the creek mouth, beyond the range of the radar, and were not constrained to following the course of the creek. Along such open coastlines radar counts at single stations would significantly underestimate birds entering watersheds, but could still be used to show relative densities and temporal variations. If the radar was moved to scan successive overlapping circles along the coast, the incoming birds could be more accurately mapped and tallied. Alternatively, the radar's scanning range could be increased, but that might require more specialized equipment than standard marine surveillance radar.

Marbled Murrelets entering a watershed might not necessarily nest there, but could cross into adjacent watersheds (Rodway et al. 1993b). Where this is likely, given the local topography and habitat distribution, radar censusing could be supplemented by audio-visual surveys. In the Bedwell-Ursus, for example, audio-visual surveys suggested that the bulk of the birds counted by radar at the Bedwell mouth were using the Ursus rather than the Bedwell valley for nesting (Figs. 5 and 6). The high proportion of subcanopy and circling detections, indicating near-nest behaviors (Paton 1995), found in the Ursus, and the absence of such behavior in the Bedwell, reinforced that conclusion (Burger et al. 1995). Audio-visual surveys on ridges and passes could also provide evidence of murrelets crossing into adjacent valleys (Rodway et al. 1993b).

The radar equipment used in this study was purchased second-hand for less than US$3,000 and could be disassembled for transportation by van, boat, or aircraft. It could be connected to a video recorder, but for logistical reasons I did not use that option in this study. Interpreting the images on the screen requires some practice. At each station it is advisable to do a pilot survey to determine the optimum position of the antenna, and familiarize the observer with the radar landscape and flight paths used by the murrelets. Birds of other species likely to be confused with murrelets should be counted.

Interpreting the audio-visual detections.—Audio-visual surveys based on the PSG protocol are the standard tool used to determine occupancy in forest stands and quantify activity levels of Marbled Murrelets (Paton 1995, Ralph et al. 1994). Since the protocol is involved in contentious and economically important land-use decisions in the Pacific Northwest, it is important to understand its strengths and limitations. This study confirmed that audio-visual observers missed a large proportion of the flying murrelets (Hamer et al. 1995), did not accurately monitor the diurnal timing of murrelet flights, especially at dawn, and did not detect the large influx of mostly silent birds arriving before sunset for incubation exchanges and chick-feeding. At my study sites, darkness prohibited visual detections earlier than 30 min before sunrise, and few audio-detections were made then, suggesting that most of the incoming birds detected by radar at this time were silent. This means that audio-visual detections of murrelets, and in particular detections of sub-canopy activities (Paton 1995), are a highly conservative measure of stand occupancy and probable nesting.

Radar is unlikely to replace the PSG protocol, because it is less effective in broken, hilly country. Most importantly, radar does not detect murrelets flying below or just above the forest canopy, and so cannot provide evidence of occupancy of forest stands (Paton 1995, Ralph et al. 1994). Ground observers are also far more likely to detect murrelets landing at or leaving nests. Radar provides limited information on flock size, altitude, and flight behaviour and no information on vocalizations, all of which are key elements to understanding the bird's behavior and habitat requirements. Radar is valuable for estimating numbers of birds entering watersheds, and hence indicate the relative importance of the inland areas as nesting habitats, and for studying temporal and spatial patterns of flight activities.

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