Spruce Budworm Moth Flight and Storms: Case Study of a Cold Front System

R. B. B. Dickison, Margaret J. Haggis1 and R. C. Rainey F.R.S.

Department of Forest Resources, University of New Brunswick, Fredericton, New Brunswick, Canada E3B 5A3

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ABSTRACT

Field studies in New Brunswick on the dispersal and redistribution of night-flying spruce budworm moths have made particular use of detailed synoptic analysis, weather radar (ground and airborne), and airborne Doppler wind-finding; moth-sampling by light-traps, pheromone-traps and aircraft-trapping; insect-detecting radar; and experimental forest spraying. By these means moths have been recorded arriving in very large numbers, with mesoscale wind systems associated with rainstorms. A case study is presented of such an influx in western New Brunswick in association with wind shifts and weather at an active cold front in July 1975.

1. Introduction

This paper reports an application of synoptic and aeronautical meteorology to one aspect of multidisciplinary studies of the ecology of a major North American insect pest. Destruction of mature softwood forest by defoliation by the spruce budworm (Choristoneura fumiferana [Clem.]) can have major consequences for the economy and employment of regions such as the province of New Brunswick which are highly dependent on the forest industry. Research on this pest, in progress on a substantial scale for more than 30 years (see, e.g., Morris, 1963), is now developing on an international basis (CANUSA, 1978). The annual displacement and redistribution of budworm populations take place during a single period of flight by the adult moths, spanning about one month during the summer. Recognition of the crucial importance of this flight activity in relation to the management of the pest led to four seasons of intensive field research (Greenbank et al., 1980), using facilities which for the first time included radar and specially instrumented aircraft.

The present paper is concerned with one particular frontal system on which the aircraft observations were made of wind shifts and precipitation in the immediate vicinity of a site where budworm moth immigration was being specially monitored (Miller et al., 1978). Evidence is presented that with the passage of these wind-shift lines and precipitation, substantial moth immigration was recorded at the special test site, and that spectacular moth invasion was observed elsewhere during that night.

Occasional occurrences of spruce budworm moths at spectacularly high densities over limited areas have been recorded in New Brunswick as far back as 1912 (Tothill, 1922). Such events have most often been attributed to cold fronts and associated thunderstorms, whose effects on budworm moth flight have been recognized by several investigators (Henson, 1951; Wellington, 1954; Greenbank, 1957). Further appearances of flying moths at high density near the ground in association with particular rainstorms and thunderstorms have been described by Greenbank et al. (1980).

2. Equipment and data

During the field studies of 1973–76 the routine meteorological observations and budworm surveys of New Brunswick and neighboring areas were supplemented by the coordinated use of special radars and appropriately equipped aircraft. Weather radars, ground-based and airborne, record radar echoes from precipitation efficiently but are not designed or operated to record insect echoes efficiently. In particular, they are normally operated with long radar ranges and are not designed to record close-in (short-range) echoes. Marine radars, on the other hand, are designed to have good close-in “seeing” ability, use short radar pulses that provide high spatial resolution, and are quite readily adaptable to the detection of insects and birds. Circuitry can be added to any radar to detect the variation in echo amplitude caused by the wingbeat of insects and birds. Such a feature is highly desirable for an insect-detecting radar but is normally not available in a weather radar. The insect detecting radars (Schaefer, 1976; Greenbank et al., 1980) were basically 3.18 cm marine sets, modified in particular...
by the provision of a parabolic reflector. For ground use this reflector was a rotating antenna system 1.5 m in diameter, and with an adjustable vertical angle; it was routinely operated to provide regular profiles of density of airborne insects. An airborne insect-detecting radar incorporating the same type of marine radar but with an antenna pointing vertically downward, has subsequently proved most useful in other such studies of insect movements (Schaef er, 1979), but was not available at the time of the present study. During the 1975 season, with which the present paper is concerned, one ground-based radar was operated at the field research base at Juniper to help monitor moth reinvasion into a test area there, and a second similar set at Chipman (for locations see Fig. 1).

Insect-collecting gear, designed at the Cranfield Institute of Technology (Spillman, 1980) to sample and soft-land airborne insects (Fig. 2), was fitted on several aircraft. Nets with a throughput of 200 m³ min⁻¹ were mounted on Cessna 185 aircraft operated nightly from Chipman and Juniper to sample the airspace at heights of 60–300 m above ground; similar equipment, with a throughput of 290 m³ min⁻¹, was mounted on the DC-3 described below.

Supplementary meteorological observations were made with a chartered geophysical survey DC-3 air-

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**Fig. 1.** Winds measured by Doppler-equipped aircraft over New Brunswick, 4 July 1975, showing frontal traverses with main precipitation areas seen on airborne weather radar at 2100 ADT and probable source area of spruce budworm moths.
craft, equipped with a Bendix Doppler radar navigation and wind-finding system (with a Northway map-presentation flight log), a standard aircraft weather radar system (Bendix RDR-1B), Statham CA 3 accelerometer, and ambient temperature and humidity recorders. A basic flight pattern of Fredericton—Grand Falls—Bathurst—Moncton—Fredericton (Fig. 1) was flown nightly over the seasonal period and at the time of night of the main flight activity of the moths. Except when flying under instrument rules, repeated sawtooth changes of course, by 60° and 120°, were superimposed on the basic flight pattern to permit multiple-drift wind-finding and to provide a continuing check in particular on airspeed corrections, in a manner found necessary in earlier work (Rainey, 1970, 1972) and in GATE experience (Grossman, 1977).

In addition to providing routine observations, the Atmospheric Environment Service (AES) of Canada provided supplementary pilot-balloon and minisonde observations in the Chipman area, with shorter periods of kytoon and acoustic sounding observations, and a network of temporary additional surface stations for studies on sea breezes. Weather Radar Reports from the FPS 77 weather radar at Loring Air Force Base in the neighboring state of Maine provided particularly useful additional information.

Spruce budworm moths, approximately 10 mm in length and weighing about 35 mg, were individually visible in flight on the insect-detecting radars up to a maximum range of 1300 m, and in high densities could be seen at low angles of elevation up to distances of 30 km. Individual echoes were found to be modulated at the wing-beat frequency (25–42 Hz) of the budworm moths, and interpretation of the radar observations was further facilitated by the fact that extensive aircraft trapping showed that spruce budworm moths enormously outnumbered any other airborne insects of comparable size over the areas and periods under consideration. The moths could not, however, be recognized among radar echoes from precipitation.

Evening take-off and other flight activity of the moths were recorded visually from observation platforms some 5 m above the general forest canopy at both Chipman and Juniper in 1975; observations at the former site were continued after dark by the use of a Rank SS32 night-viewing telescope with which individual budworm moths could be seen in flight up to distances of 50 m. At Juniper a special field experiment had been laid out to monitor and assess the immigration of budworm moths (Miller et al., 1978). A 4000 ha test block of budworm-infested forest had been intensively sprayed against the larvae, so that the subsequent population of pupae there had been only one-tenth of that in nearby unsprayed forest (and half of that in adjacent forest which had received the normal operational spraying). Production of moths within the test block was accordingly minimized, so that any moths subsequently observed there would necessarily be very largely immigrants. Moth activity and abundance over and in the test block were monitored by the ground-based insect-detecting radar in a clearing adjacent to the block, by 25 pheromone-traps using synthetic female sex-attractant (Sanders and Weatherston, 1976), and by two light traps. One light trap was sited in a clearing at the edge of the block primarily to record immigration (Greenbank, 1957; Greenbank et al., 1980), the other was suspended within the forest canopy to record more localized moth flight.

3. The cold front of 4–5 July 1975

a. Meteorology

On the evening of 4 July 1975 a front from a wave over Hudson Bay trailed southeast to a very weak low pressure area, which had approached New Brunswick from the northwest and was centered about 100 km northwest of the province at 2100 ADT (all times ADT, i.e., GMT–3 h). The Canadian Meteorological Centre (CMC) analysis (Fig. 3) showed the associated front in an arc from the northwest to an east-west orientation through northern Maine, terminating near the New Brunswick border. A cold upper trough extending from western Labrador through Maine thence southwestward contributed to very unstable atmospheric conditions.

The DC-3 encountered a clearly defined wind-shift and temperature change at about 2130 along a line nearly north–south through northwestern New Brunswick (Fig. 1). In view of the weather radar reports from Loring AFB, evidence of frontal passages at Caribou and Houlton, and the isallobaric field, this position has been fitted as an extension and curvature of the front shown in the CMC analysis to produce the analysis shown in Fig. 4.
Loring AFB at 2135 ADT reported extensive (5/10) radar echoes from precipitation in all directions from the station at ranges up to 220 km; the three precipitation cells with maximum tops were to the southeast of Loring, over high ground (Figs. 1 and 4). The central and most intense of these cells—or, more correctly, clusters of cells—was located 20 km north of the Juniper radar and test block and was shown by the Loring radar to have a top of 11 600 m, 1200 m above the tropopause. Penetrations into the stratosphere of this extent must be accompanied by exceptionally strong vertical velocities. This same cluster of cumulonimbus cells, and the northernmost one also, had been clearly depicted on the DC-3’s weather radar (Fig. 1). At Juniper there was very heavy rain between 2125 and 2240, corresponding with the passage of the southernmost of the three clusters of cells recorded to the southeast of Loring; the maximum echo top of this cell was 10 700 m. At Chipman (out of range from Loring) there was also very heavy rain, between 2340 and 0040. Precipitation was widespread across the province; the highest 24 h total was 36 mm, at Allardville, 20 km SSE of Bathurst, within the area where the DC-3 had to make a number of changes of course to avoid storms. The aircraft passed through the frontal surface twice, just north of Juniper at 2109 and 70 km northeast of Grand Falls at 2205 (Fig. 1), giving an alignment corresponding with that of the main cells seen on the weather radars in this area at the time, and in a manner similar to the arrangement of the line convection cells along particular surface cold fronts observed by James and Browning (1979) in the United Kingdom and by Hobbs and Biswas (1979) in Washington State. The first traverse, at about 845 m MSL, was marked by a wind shift from 200° at 17 kt to 295° at 13 kt within 7 km, crossing the front obliquely; the second passage, at about 1100 m MSL, exhibited a somewhat smaller wind shift, from 305° at 10 kt back to 230° at 6 kt within 5 km. Differences in air temperature and humidity were also more evident at the lower level, giving a wet-bulb potential temperature
difference of about 2°C in 9 km. The airspeed of the aircraft was nearly constant, so that this difference was not attributable to differences in the dynamic heating correction.

Whether the DC-3 encountered the front again between Moncton and Fredericton is uncertain; between 0000 and 0024, approaching Chipman, the winds gradually veered about 10°, with fluctuating temperatures that showed a net 2°C drop during this period. Wind at the Chipman 24 m tower, previously SSW, changed to WSW at 2355; and the 2400 Chipman minisonde showed that winds had veered and temperatures fallen since 2300 (Fig. 5) which may also perhaps be interpreted as further evidence of the passage of a front, though these local effects were complicated by the rain. All Chipman observations were terminated by 0050 on the 5th.

b. Effects on budworm

The night of 4–5 July 1975 was one of massive budworm moth immigration at Juniper (Miller et al., 1978). The light trap in the clearing there caught 2870 budworm moths, 1150 of them females—in both respects the highest catch of the season in this trap. This relatively high sex ratio of 40% females in a light trap catch is also circumstantial evidence of the moths being immigrants rather than of local origin (Greenbank, 1957; Greenbank et al., 1980). Emigrating moths, on the other hand, range from 61% females.

Fig. 4. Detailed supplementary surface analysis of Maritimes area, incorporating aircraft observations and weather radar observations.

Fig. 5. Minisonde observations of air temperature over Chipman 2100–2400 ADT 4 July 1975.
in airborne insect traps to 79% females in observations from platforms at canopy-top level (Greenbank et al., 1980). These findings were in striking contrast with the catches of only two budworm moths taken on both the previous and the following nights. The number of 785 male budworm moths caught in the pheromone traps on the night of 4–5 July similarly showed a highly significant increase ($P < 0.01$) compared with previous nights.

On the Juniper radar moths were already seen in small numbers up to 450 m AGL (690 m MSL) at 2010 ADT, and in somewhat larger numbers 40 min later (Fig. 5); they appeared in increasing numbers at 580 m (820 m MSL)—which was the highest level routinely monitored by the radar for insect densities—a few minutes before the radar observations were interrupted by the rain starting at 2125 with the close approach of the front. It was subsequently concluded (Miller et al., 1978) that the maximum moth densities in the airspace above Juniper had probably been missed by the radar because of its curtailment of its operations. At 2240, immediately after the rain had stopped, the Juniper radar indeed recorded high-flying moths at exceptional densities, with a volumedensity of $1.2 \times 10^{-3}$ m$^{-3}$ at 820 m MSL, which was the season’s highest value for this level at Juniper; the moths recorded in this complete profile were flying at a mean height of 700 m MSL.

At lower altitudes the Juniper radar recorded still higher moth densities, reaching a maximum of $1.8 \times 10^{-3}$ m$^{-3}$ at 260 m AGL (500 m MSL) at 2310 (Fig. 6), immediately ahead of the next rainstorm. The actual catch was of spruce budworm moths by the DC-3 between 5 and 60 km behind the front at 840–1070 m MSL (two budworm moths in 30 min, equivalent to a density of $0.2 \times 10^{-3}$ m$^{-3}$), collected without penetrating active cumulonimbus cells, was roughly consistent with the ground-based radar determinations for the lower altitude. The adverse flying conditions precluded operations by the Juniper-based Cessna on this night.

Local moth emergence had only recently begun at Juniper, with the first recorded female emergence on 1 July, but the winds found by the DC-3 ahead of the front (Fig. 1) were blowing directly from the area of the earliest budworm emergence in the province, along the St. John valley west of Fredericton, and only 50–100 km upwind from Juniper, i.e., within 1–2 h of moth flight in these winds. Further evidence of budworm moth flight out of this same area of early emergence was provided by the radar at Chipman, where high-flying moths (above 300 m AGL) were recorded in the highest numbers for the season, after midnight on 4–5 July. The Chipman radar observations had been interrupted by the heavy rain between 2340 and 0040 (on the 5th)—incidentally one of the only two such periods during the 1975 season when radar measurements of insect density could not be made at Chipman. The Cessna there managed a 12 min collecting run beginning at 2358, at 300 m, with a total catch of five budworm moths, equivalent to a density of $2 \times 10^{-3}$ m$^{-3}$.

Immediately following the rain, at 0045–0050, the highest moth densities for the season at all three top levels (340, 450 and 580 m AGL) at Chipman were recorded (Fig. 6), contributing to a total of 41000 moths per hectare—the highest area density for the season at this time of night.

Moth immigration on the night of 4–5 July was not confined to, nor most spectacular at, Juniper or Chipman. At 0130 ADT that night an isolated all-night service station at Hardwood Ridge, 100 km southeast of Juniper, was forced to close because “millions of moths” around its lights were blinding passing traffic, and next morning moths, mostly still alive, were ankle-deep beneath the lights (Greenbank, personal communication, 1975); 73% of the budworm moths were female, indicating a substantial contribution from immigrant (as opposed to local) populations (Greenbank, 1957; Greenbank et al., 1980). The moths had first appeared suddenly at 2330 ADT, coincident with a thunderstorm which was also seen as one of several rain cells observed on the insect-detecting radar at Chipman, 9 km to the east. This extreme moth concentration was highly localized; no such mass invasion was noted at Chipman nor at a temporary pilot-balloon station 5 km south of Hardwood Ridge.

![Fig. 6. Radar profiles of moth density at Juniper and Chipman for night of 4–5 July 1975 (courtesy G. M. Schaefer). Chipman observations 2140 ADT illustrate profile typical of undisturbed conditions (Schaefer, 1976).](image-url)
Further significant moth immigration was inferred by Miller et al. (1978) from the Juniper radar and light-trap and pheromone-trap records to have occurred there on four more of the following eight nights (with clear radar evidence on three of them). Egg-laying was subsequently found to have been just as heavy within the test block as in the surrounding forest. Thus immigration, particularly conspicuous on these five nights, had completely swamped the effects of the differences in larval spraying.

4. Discussion

Accumulations of flying insects in zones of wind convergence have long been recognized on the synoptic scale, with early order-of-magnitude estimates of the rates of concentration of airborne insects to be expected from likely values of convergence and the simplest of assumptions on the behavior of the insects involved (Rainey, 1951, 1963). On the mesoscale, occurrences of airborne insects at high densities at wind-shift lines have been demonstrated particularly strikingly by ground-based radar (Schaefer, 1970, 1976) and at the Fundy sea-breeze front in New Brunswick by airborne insect-detecting radar (Greenbank et al., 1980), as well as by light traps (Haggis, 1971) and suction traps (Bowden and Gibbs, 1973). Thus detailed quantitative evidence is now available on the process by which airborne insects, likely to be restricted to relatively low levels, e.g., by effects of air temperature on flight activity, can be concentrated by the low-level wind convergence, on scales likely sometimes to be biologically significant in the population dynamics of the species (Rainey, 1976; Haggis, 1983). Thus airborne insects envisaged as constrained against ascent, but otherwise without systematic motion of their own relative to the air, experiencing wind convergence at a constant rate \( c \), and considered first in an area fixed relative to the ground, would be concentrated from an initially uniform area density \( \beta_0 \) to a mean density \( \beta_r \) within this area, after time \( t \), at an initial rate given by \( \beta_r = \beta_0 (1 + ct) \). If the reference area is envisaged instead as moving with the winds, and therefore decreasing in extent because of their convergence, the density after time \( t \) will be \( \beta_r = \beta_0 e^{ct} \) (Cochemé, 1965). On 10 July 1973, for example, a quadrilateral pattern flown by the DC-3 around Chipman straddled a segment of a front which had moved inland as a minor wave from a weak warm front over Northumberland Strait (Rainey, 1976), and the winds found on this flight gave convergence at a rate of \( 8 \times 10^{-2} \) s\(^{-1}\) or 0.28 h\(^{-1}\), averaged over the 6800 km\(^2\) covered by the whole quadrilateral (and probably at least an order of magnitude greater in the immediate vicinity of the front). On the assumptions indicated, such a value of convergence could have been expected to be concentrating airborne moths at a rate giving an initial 28% increase in their area-density per hour within the fixed quadrilateral, and 32% per hour relative to the corresponding reference area contracting as it traveled with the convergent winds. This particular evening was indeed recorded by visual, light-trap and radar observations at Chipman as one of noteworthy moth flight (Rainey, 1976).

In a comprehensive and valuable review, incorporating a number of preliminary findings from the 1973–76 New Brunswick field studies, Clark (1979) concludes that moth concentration by "... line convergence resulting from cold fronts, sea breezes, and the like... is sufficiently likely to alter [budworm] outbreak release and propagation characteristics of the local system that its further study appears warranted," but considers, on the evidence available to him, that "point source convergence, represented by thunderstorms, will effect very high concentrations at very small scales, but is probably too rare and localized to influence long-term characteristics of [budworm] system dynamics." The present study has shown that although the spectacularly high moth densities seen on the ground at Hardwood Ridge were recorded only at that point, there was evidence of important moth immigration at the same time into the experimental area at Juniper, associated with the passage of a storm which in terms of echo top was not the most vigorous one recorded that night; the radar evidence of moth flight at exceptional heights and densities at Chipman as well as Juniper likewise suggests that moth concentration by the weather of that night affected a considerable area.

The weather systems considered in the present paper are spatially and temporally more complex and erratic, for example, than the Fundy sea-breeze front in the study already on record (Schaefer, 1979; Greenbank et al., 1980) and involve precipitation which masks insect echoes and complicates aircraft operations. Here, therefore, evidence is necessarily less complete and interpretations of relationships between insects and weather factors must be more tentative. Nevertheless these findings illustrate the relevance of synoptic features such as the cold front which had been recognized in the routine analysis, as well as the contributions which can be made by weather radar and aircraft wind-finding, to the improved understanding and perhaps to the management of this major pest. The aircraft and radar observations have shown spruce budworm moths at unusual and sometimes exceptional heights and densities in the immediate vicinity of particularly vigorous cumulonimbus, on occasions on which moths have appeared at very high densities on the ground, including instances of significant immigration from considerable distances. This would indeed suggest some process of concentration of the moths in flight, such as by wind convergence, known to be vigorous at low levels both during the initial stages of cumulonimbus development and at the leading edge of cold outdrafts.
The inflow towards a severe thunderstorm originates in a shallow layer close to the ground, typically 500 m deep, a few tens of kilometers ahead of the storm, and increasing in depth toward the storm (Browning et al., 1976). “Convergence in such regions is typically $10^{-3}$ s$^{-1}$. Probably this accounts for the observed increase in the concentration and depth of the moths just ahead of the Juniper storm” (Browning, personal communication, 1979), given that the moths are likely to be constrained against unlimited ascent by effects of lower temperatures on flight activity. While the particularly high moth densities at both radar stations were recorded immediately after rain, on at least one occasion they could have been attributed to convergence ahead of the next rainstorm. Browning has further pointed out that the subsequent history of the moths after that air entered the storm may have been somewhat analogous to the fate of wind-raised dust particles carried into Colorado and Nebraska thunderstorms by the low-level inflow; the dust particles became incorporated as layers within hailstones in which they could be subsequently detected and assessed (Rosinski et al., 1976). There is certainly evidence of small insects becoming incorporated in hydrometeors: a small chironomid midge was found enclosed in an ice crystal from a fall of such crystals from a small banner cloud over a 2400 m mountain in Banff National Park, Alberta (Henson, 1952), and insects have also been found in hailstones (Knight and Knight, 1978). Although only a few insects have, in fact, been detected within hailstones, it is possible that some may be trapped within smaller hydrometeors which melt before reaching the ground (Browning, personal communication, 1979).

Now that it has been confirmed that spruce budworm moths are airborne during thunderstorms, a crucial factor remaining to be explored is the mechanism whereby the moths are returned to the surface. If they were swept out by thunderstorm downdrafts they might be spread to the limits of the associated gust front; if they were washed out (literally) at the onset of precipitation, the zone of deposition would be very localized. (The insects at Hardwood Ridge may perhaps have been an example of this.) Which of these alternative mechanisms is operative may be the factor which determines whether thunderstorms are significant in the overall population dynamics, considering Clark’s views concerning the critical minimum size for budworm epidemic breakthrough (Clark, 1979).

It has been suggested (Greenbank et al., 1980) that the New Brunswick moths may well have been brought down by the rain shafts and the associated downdrafts to provide localized areas of grounded moths as at Hardwood Ridge: Browning comments

“In your case I suspect that the moths would have been washed out and deposited in locally heavy concentrations. Some may have escaped from the precipitation areas and may have been dispersed by the downdraft air, but I doubt that many would have entered the storm directly via the inflow to the downdraft since this mainly originates at rather higher levels. Thus an important mechanism of transfer of the moths from the convergent warm low-level inflow ahead of the storm to the post-storm boundary layer would appear to be via precipitation particles which grow initially in the warm rising inflow air and subsequently fall into the colder descending downdraft air. Some moths are also likely to be transferred by turbulent mixing of updraft and downdraft air at the interface between these two flows within the thunderstorms.”

The fact that the moths grounded at Hardwood Ridge were alive would moreover be consistent with their not having reached the levels of the echo tops in these storms, where temperatures were around $-55^\circ\text{C}$ at the tropopause at 10 km; moths are not likely to survive such temperatures, though the overwintering larvae regularly withstand temperatures down to $-40^\circ\text{C}$ (Mott, 1963).

5. Conclusion

The use of aircraft equipped with Doppler navigation radar and weather radar makes it possible to establish the precise location and dimensions, and subsequent development, of particularly notable and potentially significant rainstorms and thunderstorms during occasions of dispersal of spruce budworm moths and to measure in detail the associated wind fields which may concentrate these moths horizontally. In the case reported herein, airborne moth densities from catches in insect traps mounted on aircraft provided confirmation of estimates of airborne moth densities from ground-based radar observations; the evidence demonstrates that moths were flying particularly high and densely in the immediate vicinity of the storms. The fact that these storms were found to be clearly organized and that the mesoscale observations could be related to the cold front, which had been independently identified by the routine synoptic analysis, emphasizes the importance of such analyses as tools for studying and monitoring spruce budworm moth dispersal and distribution, though the moth concentrations may not be detected at the time near the ground. Further case studies of thunderstorm effects on insects are being undertaken from information which is now available from the four seasons of field work in New Brunswick.

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