

Spray deposition in relation to endosulfan resistance in coffee berry borer (*Hypothenemus hampei*) (Coleoptera: Scolytidae) in New Caledonia

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Abstract *Hypothenemus hampei* (Ferrari), in *Coffea canephora* var. *robusta* grown in New Caledonia, is controlled by applying endosulfan using vehicle-mounted mistblowers operating from roadsides. Spray deposit profiles across fields of shaded and unshaded coffee were measured by a surface fluorescence technique. In unshaded mature coffee plantations a small mistblower deposited 90% of the spray within the first 10 m from the roadside, whereas a large mistblower deposited 50% to 15 m and 90% to 30 m. The range of this large sprayer was reduced in shaded traditional plantations and was severely affected by windy conditions. Susceptible and resistant beetles, arranged in transects perpendicular to the roadside, were exposed to a standard application of endosulfan. Complete mortality of susceptible beetles occurred over the first 20 m for beetles contained in filter paper packets, compared with 10 m for beetles in green berries and 5 m for beetles in dry berries. Resistant beetles had significantly greater survival at all distances. Differential selection pressure, estimated by the differential mortality of resistant and susceptible beetles, was at maximum 6 m from the roadside. The correlation between the heaviest spray deposit and greatest selection for resistance near the point of application, is discussed.

Keywords *Hypothenemus hampei*; coffee; endosulfan; resistance; pesticide application; air-assisted spraying; mistblowers

Introduction

Endosulfan resistance is present in *Hypothenemus hampei* (Ferrari), known as coffee berry borer (CBB), in New Caledonia (Brun *et al.*, 1989). As this species is the only insect pest requiring control in coffee in New Caledonia, and coffee is the major cash crop of Melanesian farmers, CBB control is conducted nationally during the months of January and February as a service of the Agence de Développement Rural et d'Aménagement Foncier (ADRAF).

The resistance is currently confined to five regions on the East Coast of the island, although it is already very widely distributed in the two largest coffee-growing areas around Poindimié and Ponérihouen (Brun *et al.*, 1990). Resistance has been shown to be highly correlated with a recent history of endosulfan usage, and was more prevalent in unshaded, compared with shaded, plantations (Brun *et al.*, 1991). The frequency of the resistant phenotype has been demonstrated to be significantly higher near the roadsides, the point of spray application, in comparison with the far side of fields (Brun and Suckling, 1992).

The aim of this study was to measure spray deposit patterns in newer unshaded plantations and traditional shaded plantations, and to relate these patterns to the efficacy of endosulfan. From this, it was hoped to gain insight into the selection pressure resulting from the roadside spraying of the coffee. An earlier paper (Parkin *et al.*, 1991) reported on some measurements of spray distribution, and examined the variability of deposit; this paper examines more closely the spray distribution patterns, presents comparative efficacy data and examines the link between deposit and endosulfan resistance.

Materials and methods

Spray equipment and application details

The spraying of coffee in New Caledonia is carried out from roadsides because individual application by pedestrian-operated sprayers would be difficult with the uneven terrain and dense foliage of most areas. Two models of vehicle-mounted mistblowers are in service with ADRAF.

For small areas of unshaded plantations, a small mistblower, a BSE Mk IV mistblower (Bernhard Shulze-Eckel

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Mascinenfabrik, Ahlen, Germany), mounted on a light truck, is used. This consists of a petrol engine-driven centrifugal fan which generates an air-jet of $1.5 \text{ m}^3 \text{ s}^{-1}$ at 113 m s^{-1} velocity (nominal). Four 2.5 mm orifice diameter hollow-cone nozzles mounted on a ring around the fan outlet project spray into the air-jet. The height of the outlet, which is usually projected horizontally, is $\sim 2.5 \text{ m}$ above ground level. A flow calibration showed that each of the spray nozzles emitted 94 ml s^{-1} at the 20 bar (2000 kPa) operating pressure. This gives an application rate of 1741 ha^{-1} over a 25 m swath at a typical forward speed of 3 km h^{-1} .

Most of the spraying is carried out in areas where coffee is grown traditionally, i.e. under shade from a native forest canopy. In these areas a large mistblower, the BSE Super Bangui (Bernhard Shulze-Eckel Mascinenfabrik, Ahlen, Germany) mounted on a heavy truck is used. The Super Bangui is driven by a diesel engine and has a centrifugal fan which generates $7.8 \text{ m}^3 \text{ s}^{-1}$ of air at 125 m s^{-1} (nominal). A ring of six 2 mm orifice diameter hollow-cone nozzles surrounds the air outlet. The nozzles were also operated at ~ 20 bar pressure. A flow calibration showed that each spray nozzle emitted 79 ml s^{-1} . At a swath of 45 m (Decazy, 1988), this gives an application rate of 1251 ha^{-1} at a typical forward speed of 3 km h^{-1} . The height of the outlet of the Super Bangui was 3.3 m above ground.

The standard spray treatment for CBB control in New Caledonia is a 0.7% v/v concentration of endosulfan a.i. (Thiodan 35 EC, Hoechst AG, Germany) in water. This was used in all field bioassay experiments. During spraying experiments, wind speed was monitored outside the coffee fields at 2 m height by a hand-held vane anemometer (Airflow Developments, Aylesbury, England). Temperature and humidity were measured using a whirling-arm hygrometer (Casella, Bedford, England).

Experimental sites

One shaded and three unshaded fields of *Coffea canephora* var. *robusta* were used to conduct experiments. Field 1 was an unshaded plantation at Pocquereux, near La Foa on the West Coast of New Caledonia. Although recently planted (July 1985), the average tree height was 2.5 m. The interrow (between-row) tree spacing was 3 m and the intrarow (within-row) spacing was 2 m. The field measured 105 m by 50 m and was accessible for spraying along each edge. This field was used to investigate the efficacy of a packet bioassay technique, and to investigate spray deposition and response to endosulfan of a susceptible population using the small vehicle-mounted mistblower.

Field 2 was also an unshaded plantation but located at the Institut de Recherche du Café et du Cacao (IRCC) research station at Ponérihouen, on the East Coast. The field was planted in 1983 with tree spacings of 3 m interrow, and 2.5 m intrarow. Trees were 2.5 m high, and were due to be pruned to ground level within a year as they had been in berry production for 5 years. The field extended 78 m from the roadside and was used to investigate spray deposits from the large vehicle-mounted mistblower. It was also

used to assess the response of susceptible and resistant populations present in dry berries.

Field 3 was 100 m to the north-west of field 2, and was another unshaded plantation. It was also chosen to study spray deposition with the large mistblower. The trees were 2 m high, following pruning to ground level in 1987. The field also extended 78 m from the roadside and was planted at 2.5 m interrow, and 2.5 m intrarow, tree spacings.

Field 4 was a traditional shaded plantation, under a native forest canopy, located 3 km from fields 2 and 3. The tree spacing was variable, but was $\sim 5 \text{ m}$ between centres. The coffee tree shape at this site was more umbraculiform than the trees grown in the full sunlight of the newer plantations. This field was used to characterize spray deposition from the large mistblower in traditional plantations.

Spray deposit measurement

A portable spray deposit assessment technique that was capable of handling large numbers of samples was required. Standard fluorimetric techniques (Sharp, 1974), where the deposit is eluted from the deposit surface, presented practical difficulties (Parkin *et al.*, 1991); it was therefore concluded that the most suitable technique for this study was surface fluorescence measurement (Parkin and Uk, 1983).

Although it was considered desirable to measure deposition on the berries, this did not prove to be feasible for two main reasons. First, in New Caledonia, a wide size range of unripe berries is present on *C. canephora* var. *robusta* at the time of spray application, together with some unharvested dry berries from the previous season. It was impractical to modify a surface fluorimeter to cope with this range of sizes. Second, at some sample locations across a field it was possible to find trees without any berries. It was therefore deemed expedient to measure spray deposition on leaves adjacent to the growing points of the berries rather than the berries themselves.

The surface fluorimeter used for the spray deposition experiments was that developed at Cranfield (Parkin and Uk, 1983), and tested on tree crops (Cowell, Lavers and Taylor, 1988). Because a large number of deposit samples was anticipated, data from the surface fluorimeter were automatically stored on a Campbell 21X data logger (Campbell Scientific Ltd, Sutton Bonington, England) and downloaded onto a portable microcomputer. Analysis of the results was carried out by software developed at Silsoe College and by a standard spreadsheet.

It was not possible to carry out spray deposition and biological assessments concurrently, so all spray deposit measurements were made using water plus a fluorescent tracer, and all biological measurements were made with standard endosulfan applications. The tracer used was the fluorescent pigment Lunar Yellow (Swada Ltd, London, UK). This was specially formulated for use with the surface fluorimeter as a 25% v/v s.c. formulation (Shell Research Ltd, Sittingbourne, UK) and applied at the rate of 4 litres in 100 litres of water. The surface fluorimeter was calibrated to enable spray deposits to be expressed as mass

of tracer per unit area. The calibration was carried out using a Potter Tower technique (Potter, 1952). Calibration details were given by Parkin *et al.* (1991).

Sampling transects were established perpendicular to the roadsides. In all but one of the spray deposition experiments, at each sample location 10 leaves were sampled from positions around the tree. For the experiment in field 4 it was considered that there might be greater variability in deposits in a traditional shaded plantation, so 20 leaves per location were taken. For the experiments at La Foa (field 1), and the first experiment at Ponérihouen (field 2), samples were taken at three levels in the crop, but in the other fields samples were taken at two levels. Two replicate transects were sampled in the first spray deposit experiments at both La Foa (field 1) and Ponérihouen (field 2), but at all other sites, as there was little variation between transects, it was decided to restrict the samples to a single transect. Spray deposition was measured at three locations on the adaxial and abaxial surfaces of each leaf. The results for each surface, crop level and sampling point were then grouped. Thus, at least 30 measurements were made for each data point. The location of the sampling points along a transect varied between treatments and was based on visual assessment of the spray deposit and related to field size.

Biological assessment

Insect strains. The reference susceptible strain was the same as that reported by Brun *et al.* (1989), from La Foa (LA2). Both green and dry berries containing insects from this strain were used in the experiment at La Foa, whereas only dry berries were used at Ponérihouen. Two resistant strains were collected: the first, for the packet bioassay at La Foa, was from Ponérihouen (PN402), whereas the second resistant strain, tested in the berry bioassay at Ponérihouen, was collected near Poindimié (PO01). The phenotypic frequency of resistance for the strains was determined from 120 beetles from each strain using the diagnostic concentration of 400 p.p.m. endosulfan (the LC_{99.95} of susceptibles) by the direct spray method of Brun *et al.* (1989).

Packet bioassay. A pilot study was conducted in December 1989 at La Foa (field 1) to determine the efficacy of field applications of endosulfan against resistant and susceptible CBB females. Berries were opened with a sharp scalpel and beetles removed and stored overnight at 10°C in Nouméa. Thirty healthy adult females of either strain (LA2 and PN402) were placed in filter paper packets lined with fine nylon gauze and clamped on three sides with bull clips to avoid the escape of any resistant individuals. This method was essentially similar to the packet test used to monitor resistance in cattle ticks (Stone and Haydock, 1962) and was designed to estimate the mortality of free-living female CBB at the time of spray application. Packets were suspended from stakes at two heights (1 m and 2 m) at the tree interrows and in a transect downwind from the spray application. Control packets were main-

tained under similar conditions nearby. A spray application of endosulfan was made by the BSE Super IV mistblower mounted on a light truck. Packets were removed from the field after 6 h, and CBB mortality, corrected for control mortality by Abbott's formula (Abbott, 1925), was assessed at 10 and 25 h post-treatment, with interim storage at 25°C.

Berry bioassay. Infestation levels of berries by CBB in the field show a wide variation. This has led to the development of a technique where dry berries, which are known to have high infestation levels, are collected and exposed to the spray. As some escape of beetles after spraying could not be prevented, in order to avoid introducing the resistance to the West Coast only berries from the susceptible strain were used in the test at La Foa (field 1). However, both resistant and susceptible strains were used on the East Coast. Green berries, which characteristically have a much lower infestation rate than dry berries, were also used at La Foa to investigate whether there are differences in mortality caused by berry condition. In this experiment at each position along a transect, two enclosures, each containing 20 dry berries infested with a mean of 28 CBB per berry (s.e.m. = 4), giving totals of 920–1509 susceptible CBB per transect position, were exposed to a field treatment of endosulfan. In addition, at each position, two enclosures each containing 30 green berries, with a mean of 0.9 CBB per berry (s.e.m. = 0.1), giving totals of 38–87 susceptible CBB per position, were exposed.

The resistant (PO01) and susceptible (LA2) strains were used in the transect at Ponérihouen (field 2). At each position of this transect, for each strain, there were two enclosures containing 15 dry berries. There was a mean of 34 CBB per berry (s.e.m. = 2) in berries from the susceptible strain area and 30 CBB per berry (s.e.m. = 2) in berries from the resistant strain area, giving total numbers per transect position of 433–747 for the susceptible strain and 322–564 for the resistant strain.

In each case, berries were contained in fully ventilated flat plastic mesh enclosures (100 mm × 160 mm), consisting of large-gauge mesh (5 mm apertures). The CBB enclosures were hung on stakes at each of two heights (1 m and 2 m). The stakes were set within the row, close to the normal location of the berries. After spray application, berries were left for 3 h before being collected and stored in open plastic bags, and then left for 48 h on a bench at 25°C. Berries were removed from the field to avoid rain. The bags were left open to prevent fumigation, but were orientated with the closed end towards the light, to trap emerging beetles. CBB mortality was again corrected for control mortality by Abbott's formula.

The berry exposure technique was found to be more convenient and robust than the packet bioassay technique, as well as being more representative of field mortality conditions, and was therefore adopted for comparison of CBB mortality with spray deposit measurements. The berry enclosures were positioned at locations in the crop based on the result of the previous spray deposition analysis.

Table 1. Summary of field experiments

| Description | Location | Date | Temp. (°C) | Humidity (%) | Wind ^a (m s ⁻¹) |
|---|--------------------------|------------------|------------|--------------|--|
| Pilot study. Packet bioassay. Susceptible and resistant strains. Mature unshaded plantation. Small sprayer. | La Foa (field 1) | 14 December 1989 | 29 | 96 | +0.7 |
| Spray deposition. Mature unshaded plantation. Small sprayer. | La Foa (field 1) | 9 January 1990 | 31 | 55 | -1.5 ^b +1.25 |
| Berry bioassay. Susceptible strain. Mature unshaded plantation. Small sprayer. | La Foa (field 1) | 11 January 1990 | 32 | 62 | +1.5 |
| Spray deposition. Mature unshaded plantation. Large sprayer. | Ponérihouen (field 2) | 17 January 1990 | 29 | 78 | +1.86 |
| Spray deposition. Young unshaded plantation. Large sprayer. | Ponérihouen (field 3) | 17 January 1990 | 29 | 78 | +2.98 |
| Spray deposition. Mature shaded plantation. Large sprayer. | Ponérihouen (field 4) | 17 January 1990 | 29 | 78 | Calm |
| Berry bioassay. Susceptible and resistant strains. Mature unshaded plantation. Large sprayer. | Ponérihouen (field 2) | 18 January 1990 | 29 | 86 | +0.89 |

^aWind component in direction of spraying; ^bplot sprayed both with and against wind (i.e. from each end of field)

Spray experiments

A summary of all the experiments is given in *Table 1*. To allow comparison, spray deposition and comparable bioassay experiments were conducted under similar meteorological conditions.

Results and discussion

Spray distribution

At La Foa (field 1), for the small mistblower on mature unshaded coffee, spray deposit patterns were measured along two transects. As there was little difference between results from the two transects, results from only one transect are shown (*Figure 1*). It should be noted that the field was sprayed from both the upwind and downwind field edges. The spray deposit patterns from the large mistblower in mature unshaded coffee at Ponérihouen (field 2), are shown in *Figure 2*. Again, only one transect is shown because there was a similar pattern in each transect. The results of the other deposit experiments with the large mistblower are given in *Figures 3* and *4*. Only the adaxial surface results are shown since there was a similar relationship between surfaces to the results in *Figure 2*.

The spray distribution from the small mistblower was very limited, even with a following wind (*Figure 1*), as > 90% of the spray deposited in the crop was deposited in the first 10 m. This was undoubtedly because the emission height of the mistblower was at, or slightly below, the tops of the trees and the air output volume is relatively low.

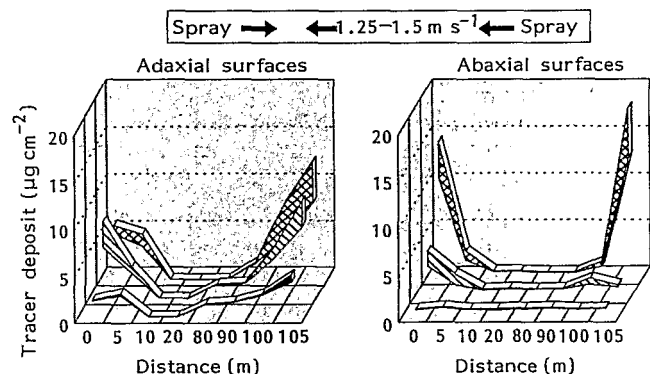


Figure 1. Deposit of tracer (95% confidence interval of the mean) on adaxial and abaxial surfaces in an unshaded plantation with distance from point of application for the small mistblower at La Foa (field 1). Level in crop: ■, lower; ▨, middle; ▩, upper

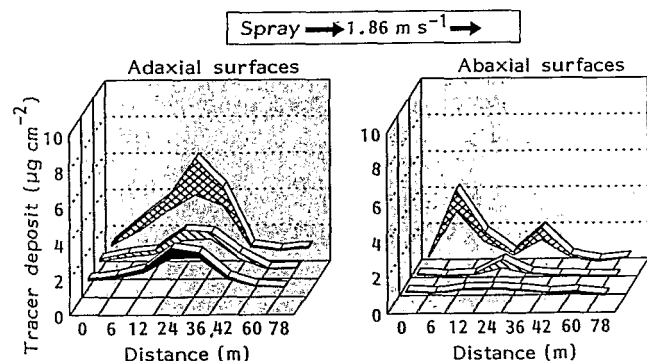


Figure 2. Deposit of tracer (95% confidence interval of the mean) on adaxial and abaxial surfaces in an unshaded plantation, with distance from point of application for the large mistblower at Ponérihouen (field 2). Level in crop as in *Figure 1*

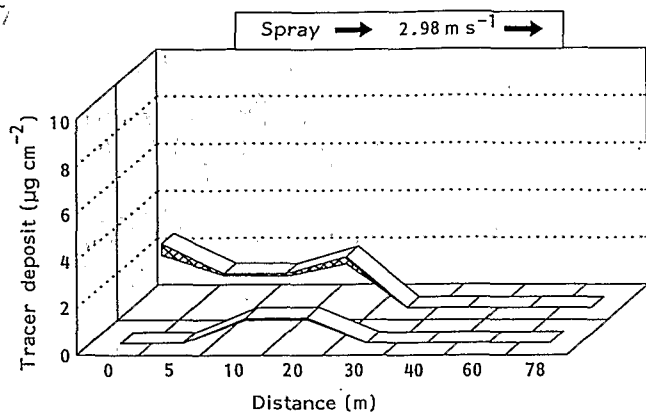


Figure 3. Deposit of tracer (95% confidence interval of the mean) on adaxial surfaces in an unshaded plantation, with distance from point of application for the large mistblower at Ponérihouen (field 3). Level in crop: ■, lower; ▨, upper

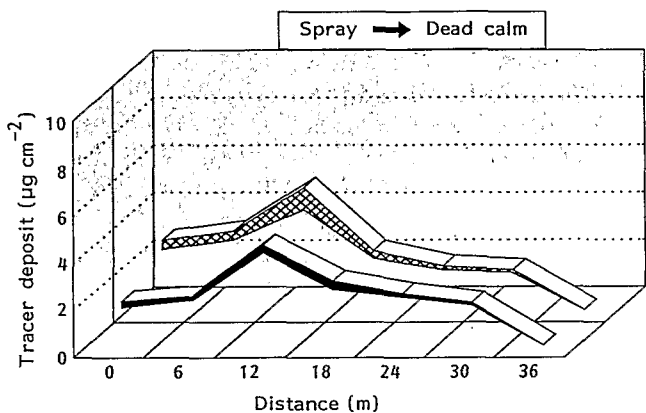


Figure 4. Deposit of tracer (95% confidence interval of the mean) on adaxial surfaces in a shaded plantation, with distance from point of application for the large mistblower at Ponérihouen (field 4). Level in crop as in Figure 3

The large mistblower, having both a greater volume of air output and a higher emission point, projected spray across the top of the canopy and provided better spray distribution (Figure 2). It was estimated, from the adaxial upper level measurements, that 50% of the spray was deposited within 15 m of the road and 90% within 30 m of the road. Its performance could be adversely affected by wind, as seen in the experiment in field 3 at Ponérihouen (Figure 3). Here, a relatively strong following wind appears to have dissipated the air-jet and diluted the spray cloud sufficiently to produce an unacceptable result. These conditions are not uncommon during routine spraying. Presumably most of the spray in this experiment drifted out of the field.

Where an air-jet projects spray across the top of a crop, as with the large mistblower, the deposition mechanism is almost entirely sedimentation. The air-jet carries spray across the top of the crop and provides the basic spray dispersal but, at some point determined by the strength and size of the air-jet, drop size and atmospheric conditions, the spray sediments into the crop. This can be seen by comparing data from the large and small mistblowers in mature unshaded plantations. With the small mistblower

(Figure 1), spray deposition on the abaxial and adaxial surfaces close to the emission point was similar. However, with the large mistblower (Figure 2), the adaxial surfaces received significantly more spray than the abaxial, indicating a more vertical, and thus sedimentary, trajectory for the spray. The advantages of having an air outlet discharging above a crop, and emitting a larger air volume, can be clearly seen.

Most coffee in New Caledonia is still grown in shaded plantations (Brun *et al.*, 1989), so the result shown in Figure 4 is significant in that it represents the most common form of application in the most common type of plantation. It appears that spray coverage in this type of plantation is still limited to areas close to the road. It was estimated that 50% of the spray was deposited within 10 m of the road and 90% within 27 m of the road.

Thus, as predicted by Decazy (1988), most of the spray from all the treatments is deposited close to the point of emission, giving a very heavy overdose of active ingredient in the first 10 or 20 m of the fields. It appears that far sides of the coffee fields receive only a small fraction of the expected dosage of endosulfan and expressions of field dosage rates per hectare are effectively meaningless in this case.

Biological assessment

Insect strains. As described earlier, the LA2 strain of CBB has been found to be endosulfan susceptible. The frequency of the resistant phenotype surviving the diagnostic dose in the PN402 strain was 64.4%, and 49% in the case of the PO01 strain.

Packet bioassay. CBB mortality in the packets increased slightly, between 10 and 25 h; hence only the results from the second reading are presented here (Figure 5) because these represent a better estimation of the full insecticide efficacy. Greater mortality resulted at 2 m, compared with the 1 m height, but the results have been grouped ($n=60$) for presentation. All susceptible beetles were killed at distances up to and including 20 m from the roadside, whereas resistant insects survived at all locations.

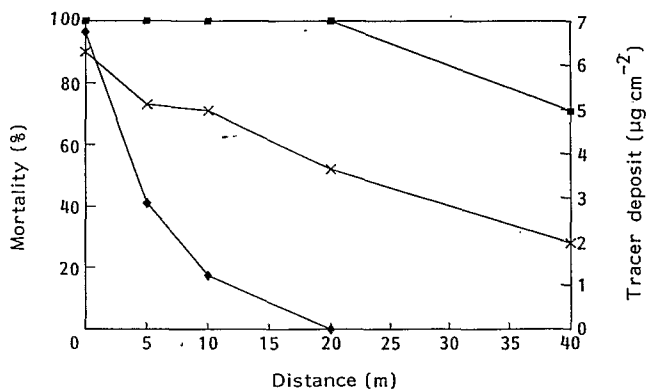


Figure 5. Percentage mortality of adult female susceptible (■) and resistant (X) *H. hampei* in filter paper packets and mean tracer deposit (all surfaces and levels, ◆), with distance from the point of endosulfan application at La Foa (field 1)

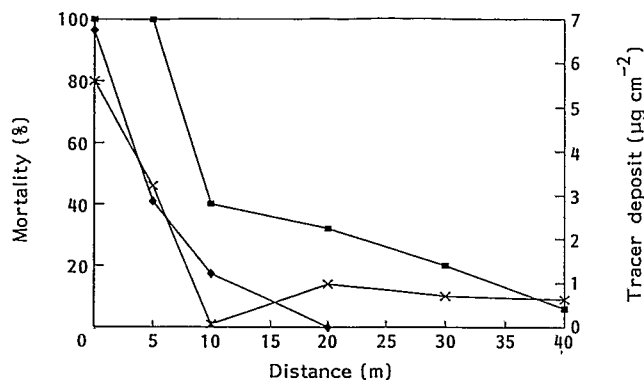


Figure 6. Percentage mortality of adult female susceptible *H. hampei* in green (■) and dry (X) coffee berries and mean tracer deposit (all surfaces and levels, ◆), with distance from the point of endosulfan application at La Foa (field 1)

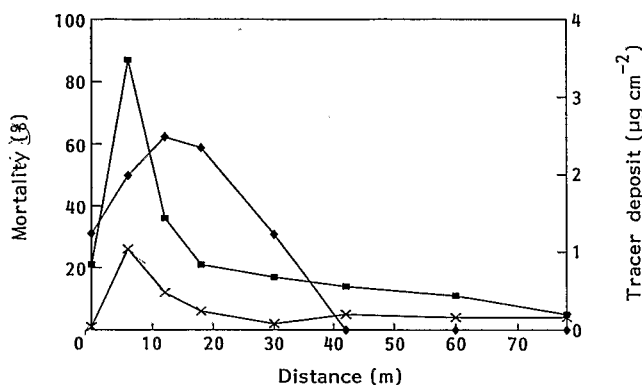


Figure 7. Percentage mortality of adult female susceptible (■) and resistant (X) *H. hampei* in dry coffee berries and mean tracer deposit (all surfaces and levels, ◆), with distance from the point of endosulfan application at Ponérihouen (field 2)

Some survival of susceptible insects occurred at 40 m from the point of insecticide treatment (Figure 5), although significantly more resistant insects survived ($\chi^2 = 19.33$, 1 d.f., $p < 0.001$), indicating that an important selection differential could exist on CBB outside berries at the time of treatment, even at 40 m from the point of insecticide application. The gradual decrease in mortality of resistant CBB with distance from the point of treatment is strongly suggestive of a mechanism for the development of the clines in resistance reported by Brun and Suckling (1992) and the rapid spread of higher frequency of resistance across the field in one year.

Berry bioassay. The mortality of susceptible CBB in both dry and green berries from the experiment at La Foa is shown in Figure 6. Each point is the mean of the berries placed at 1 m and 2 m height. The rapid decrease in mortality with distance of a susceptible population in both green and dry berries closely followed the rapid decay in spray deposition (Figures 1 and 6). The decrease of mortality is more rapid than that found in the packet tests (10 m; Figure 5) under similar, but slightly windier conditions (Table 1). This may be attributable to the technique used, as the beetles were more directly exposed to the endosulfan

(liquid and vapour) and the packets were positioned between rows, allowing for better spray penetration and vapour movement.

The differential selection pressure on susceptible and resistant populations of CBB from the experiment at Ponérihouen is shown in Figure 7. The difference in mortality between strains was significant at allocations in the field according to the χ^2 goodness of fit test (the minimum difference occurred at 78 m, $\chi^2 = 18.7$, 1 d.f., $p < 0.001$). There appears to be a low level of mortality of the susceptible population even at the downwind edge of the field. This could be explained in terms of a fumigant action. Brun *et al.* (1991) found that indirect exposure bioassays gave rapid mortality of susceptible but not resistant strains after 2–3 h at 400–1000 p.p.m. It is, therefore, likely that this mortality, with little apparent direct spray deposition, was the result of gaseous phase activity. This probably also explains why overspraying the crop at a height of 3.3 m from the roadside has little effect on the distribution of mortality in the immediate vicinity of the sprayer.

As the bioassay of the PO01 strain showed a 49% frequency of the resistant phenotype, and Figure 7 shows the resistant strain mortality at 6 m to be 26% compared with 84% for the susceptible strain, it must be assumed that some members of the susceptible phenotype were still present in the field-collected 'resistant' population. If the 'resistant' population collected in the field was composed solely of the resistant phenotype, then no mortality might have been expected at these points. To investigate further the differential selection pressure for the resistant phenotype, the mortality data of the resistant and susceptible strains were expressed as a differential mortality and subjected to an angular transformation (Figure 8). This shows that the selection pressure was greatest 6 m downwind but that some selection pressure was present across the entire field. It is not known what level of kill would be expected for heterozygotes, although the level of dominance and fitness of heterozygotes, with and without insecticide exposure, are fundamental to the rate of resistance development by populations in the field and could be expected to change with time or distance from the roadside.

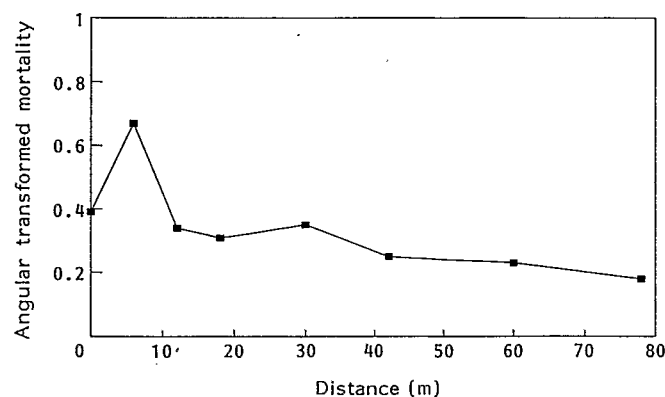


Figure 8. Mortality of adult female susceptible and resistant *H. hampei* in dry coffee berries, subjected to an arcsine (proportional mortality) transformation, with distance from the point of endosulfan application at Ponérihouen (field 2)

Implications for managing resistance

Relatively few attempts have been made to estimate selection resistance in the field. Selection for insecticide resistance in sheep blowfly has been demonstrated to change over time, owing to changes in viability of different genotypes with decaying residues (McKenzie and Whitten, 1982). One interesting outcome of this work was that the period of selection was considerably greater than the period of protection from fly strike. This concept could have a parallel in our case, where selection for resistance appears to extend a greater distance from the roadside than the distance over which the insecticide is effective at controlling susceptible beetles. In another example, resistance was not constant over time; Daly, Fisk and Forrester (1988) showed that the selective mortality of resistant *Helicoverpa (Heliothis) armigera* could be minimized by targeting very young larvae that were as susceptible to pyrethroids as were susceptible larvae, making resistance functionally recessive by correct insecticide timing. Unfortunately, no parallel period (or location) of minimum selection is likely to exist in this case, owing to overlapping generations and other factors.

Clearly, the distribution of spray within the fields is a contributory factor in the development of resistance. A more even application would be beneficial in delaying the onset of resistance, but achieving this may not be easy. Spray application to individual trees by, for example, motorized knapsack mistblower, could provide a solution, but this would require considerably more resources and organization than are currently employed. It would also increase the likelihood of pesticide contamination either through use, because of the dense canopy and uneven ground, or in mixing. It is, therefore, unlikely that this form of application could be adopted except, perhaps, on a limited scale in inaccessible areas. Thus, the current technique of using vehicle-mounted mistblowers operating from roadsides will remain the primary technique for some years. It is vital, therefore, that it is optimized and improved. It is also important that planting patterns and access to the fields be improved to achieve better application.

Any improvement in spray distribution would not necessarily delay the onset of resistance (depending on the fitness of the genotypes), but immediate steps could be taken to reduce the problem. Alternative pesticides, such as fenitrothion, must be investigated and a resistance management strategy that cycles pesticides of differing chemical types and groups should be implemented (Brun *et al.*, 1989).

The mean numbers of female CBB per green and dry berry collected during the experiments were 1 and 31.5 respectively. Thus, a large potential for reinfestation exists if dry berries are not removed at the end of the growing season. Selection for resistance is a function of the population size and level of kill. Increases in resistance frequency will depend on the relative fitness of different genotypes, with and without the presence of insecticide (Georghiou and Taylor, 1977). A higher rate of kill of CBB was observed in green berries, compared with dry berries, and

mortality extended further across fields. The application of endosulfan normally occurs at the green berry stage in New Caledonia (January and February). The higher rate of kill of beetles in green berries suggests that the resistance of the high level found in New Caledonia could be more likely to result from the selection of beetles attacking green berries. It would take longer for the population to recover, but it would be more resistant, assuming equal fitness, than a lower level of kill of beetles at higher infestation levels in dry berries. The relatively slow rate of reversion suggests that the fitness differential may not be that great in the absence of endosulfan (Brun and Suckling, 1992). Thus, the physical removal of dry berries from trees, and from the plantation floor, could have an important role in reducing the size of the population under selection, both in dry berries and as a source of infection of green berries.

Future work

Spray deposit measurements, although indicating trends, should be improved to measure directly spray deposition on berries. In addition, deposition studies should be extended to *Coffea arabica*, which is also grown in some areas of New Caledonia and has a different growth form, leaf shape and berry development. Tracer deposit studies could be confirmed by using gas-liquid chromatography technique: this would enable the amount of tracer deposited to be directly related to the quantity of endosulfan on each berry; this in turn could be related to bioassay and field efficacy results.

It may also be possible to improve the field estimation of selection pressure further by using the berry bioassay technique, as this technique has shown the ability to provide differential mortality and is sufficiently robust for field use.

It is important that biological control alternatives continue to be investigated alongside the search for improvements in spray application techniques, and the selection of alternative environmentally acceptable insecticides.

Conclusions

The link between the endosulfan resistance profile across fields and spray deposition has been clearly demonstrated, as the current models of mistblowers appear to deposit most of the spray within 20 m of the point of application. Improvements in application technique are therefore required, although it is thought that the widespread use of spray application to individual trees by pedestrian-operated sprayers is not feasible in New Caledonia.

There is a high selection pressure exerted near the roadside as a result of the high deposits and atmospheric concentration of endosulfan there, not because of the frequency of application (twice yearly). It has also been shown that the number of CBB exposed to selection in green and dry berries may be very different, and would be expected to change as a function of distance from the point of application.

Acknowledgements

The authors would like to acknowledge the support of ADRAF and the assistance of Mr J.-M. Py, Chief Opération Café – East Coast, and Messrs J. Kabar and M. Martotaroeno of ADRAF, Ponérihouen. Miss V. Gaudichon and Mr C. Marcillaud of ORSTOM, Nouméa, and Mrs D. M. Parkin provided invaluable assistance in the field experiments.

The authors are also grateful to Mr P. M. F. E. Jeggerens of Shell Research Ltd, Sittingbourne, for supplying the fluorescent tracer formulation and Mr J. C. Wyatt of the College of Aeronautics, Cranfield, for assistance with the interfacing of the surface fluorimeter.

References

- Abbott, W. S. (1925) A method of computing the effectiveness of an insecticide. *J. Econ. Entomol.* **18**, 265–267
- Brun, L. O. and Suckling, D. M. (1992) Field selection for endosulfan resistance in coffee berry borer *Hypothenemus hampei* (Coleoptera: Scolytidae) in New Caledonia. *J. Econ. Entomol.* **85**, in press
- Brun, L. O., Marcillaud, C., Gaudichon V. and Suckling, D. M. (1989) Endosulfan resistance in *Hypothenemus hampei* (Coleoptera: Scolytidae) in New Caledonia. *J. Econ. Entomol.* **82**, 1311–1316
- Brun, L. O., Marcillaud, C., Gaudichon V. and Suckling, D. M. (1990) Monitoring endosulfan and lindane resistance in the coffee berry borer *Hypothenemus hampei* (Coleoptera: Scolytidae). *Bull. Entomol. Res.* **80**, 129–135
- Brun, L. O., Marcillaud, C., Gaudichon, V. and Suckling, D. M. (1991) Evaluation of a rapid bioassay for diagnosis of endosulfan resistance in coffee berry borer *Hypothenemus hampei* (Coleoptera: Scolytidae). *Trop. Pest Mgmt.* **37**, 221–223
- Cowell, C., Lavers, A. and Taylor, W. (1988) Studies to determine the fate of low volume sprays within an orchard environment. *Aspects Appl. Biol.* **18**, 371–383
- Daly, J. C., Fisk, J. H. and Forrester, N. W. (1988) Selective mortality in field trials between strains of *Heliothis armigera* (Lepidoptera: Noctuidae) resistant and susceptible to pyrethroids: Functional dominance of resistance and age class. *J. Econ. Entomol.* **81**, 1000–1007
- Decazy, B. (1988) *Compte Rendu de Mission en Nouvelle Calédonie, 14 au 29/01/1988*. IRCC/CIRAD Report Ronéo. 29 pp
- Georghiou, G. P. and Taylor, C. E. (1977) Operational influences in the evolution of insecticide resistance. *J. Econ. Entomol.* **70**, 653–658
- McKenzie, J. A. and Whitten, M. (1982) Selection for insecticide resistance in the Australian sheep blowfly *Lucilla cuprina*. *Experimenta* **38**, 84–85
- Parkin, C. S. and Uk, S. (1983) The evaluation of aerial application systems. *EPPO Bull.* **13**, 531–534
- Parkin, C. S., Brun, L. O., Gaudichon, C. and Marcillaud, C. (1991) The use of vehicle-mounted air-blast sprayers for the control of Coffee Berry Borer in New Caledonia. In: *Air-Assisted Spraying in Crop Protection: British Crop Protection Council Monograph No. 46* (Ed. by A. Lavers, P. Herrington and E. S. E. Southcombe) pp. 277–285, BCPC, Thornton Heath
- Potter, C. (1952) An improved laboratory apparatus for applied direct sprays and surface film, with data on the electrostatic charge on atomised spray fluids. *Ann. Appl. Biol.* **39**, 1–28
- Sharp, R. (1974) Spray deposit measurement by fluorescence. *Pestic. Sci.* **5**, 197–209
- Stone, B. F. and Haydock, K. P. (1962) A method for measuring the acaricide susceptibility of the cattle tick *Boophilus microplus* (Can.). *Bull. Entomol. Res.* **53**, 563–578

Received 6 December 1990

Revised 27 November 1991

Accepted 2 December 1991